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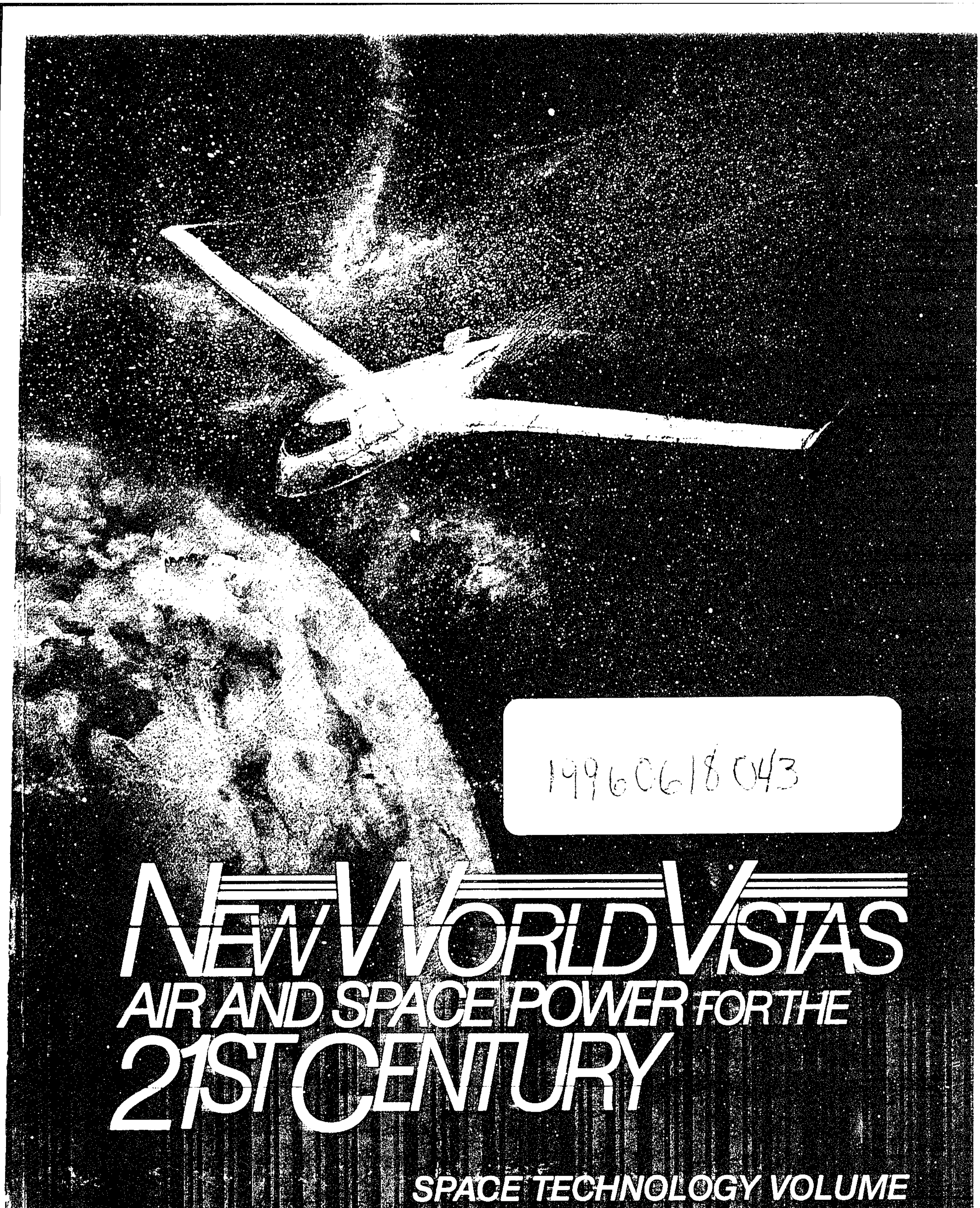

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NEW WORLD VISTAS
AIR AND SPACE POWER FOR THE 21ST CENTURY

SPACE TECHNOLOGY VOLUME

NEW WORLD VISTAS

AIR AND SPACE POWER FOR THE 21ST CENTURY

SPACE TECHNOLOGY VOLUME

This report is a forecast of a potential future for the Air Force. This forecast does not necessarily imply future officially sanctioned programs, planning or policy.

Executive Summary

An Investment Strategy for the Air Force in Space Technology for the Next Twenty Years

Vision

The Space Technology Panel's recommendations for technology investments derive from a vision of the Air Force in space in the 21st century, in which the Air Force has achieved *survivable, on demand, real time, global presence that is affordable.* This vision represents a *revolutionary* increase in capabilities for the Air Force and is achievable with targeted Air Force technology investments and adaptation of commercial developments. These technology investments will enable the US to maintain military superiority by the exploitation of space through four themes:

- Global Awareness
- Knowledge on Demand
- Space Control
- Force Application

The Current Situation in Space

Space will continue to be the proverbial high ground for the foreseeable future. Operation Desert Storm showed that space assets integrated with air, ground, and sea assets can play a critical role as force enhancers in fighting and winning conflict. Senior Air Force leadership[1] asserts that "space systems signal America's stature as a world power and aerospace nation. Control of space and access to it are fundamental to economic and military security. Ask the 20 foreign countries who will have space capabilities by the year 2000: a presence in space implies influence, power and security."

The space enterprise can be divided roughly into four areas:

- Launch systems
- Spacecraft bus systems
- Spacecraft payload systems
- Spacecraft operations

In the area of launch systems, despite the recent development of small launch vehicles, US launch capability is dominated by an old, unresponsive, and relatively expensive set of launchers. Foreign launch systems have taken a substantial fraction of the world market, and the number of countries able and willing to launch payloads is continuing to increase. In the area of spacecraft bus technology, the US is in a leading position; the one major area where other countries have taken the lead is in spacecraft propulsion, where US technology is behind what has been

1. Hon. Sheila E. Widnall, Secretary of the Air Force, September 1993

accomplished in the former Soviet Union. The US is still leading in the integration and operation of spacecraft payload systems both from the component level into spacecraft and in the development of constellations of spacecraft. *This leading position is due to previous government investments in research and development in space technology*; maintaining this lead in the future will depend on the technology investments that the US government *and* private sector make today.

The reduction of resources available to the DoD in the post-Cold War era means that DoD investment in space technologies and space systems must be firmly rooted in the goal of affordable systems. To this end, the DoD must plan its technology investment with a clear view of technological advances in the commercial world. It is undesirable and unnecessary for the DoD to develop every technology for its space systems on its own. There are many technologies that the commercial sector will develop that the military can adapt for its use with minimal investment. On the other hand, there will always be unique requirements for military systems that necessitate the use of technologies that have no commercial application, that push the performance limits of dual-use technologies, or whose timescale and risk are not attractive to the commercial sector. The DoD should carefully target its investments in technology to achieve the highest possible return. Technologies that are candidates for DoD investments fall into one of three possible categories:

- Revolutionary technologies in which the DoD must invest vigorously, because they are critical to the military mission and have little or no application in the commercial sector; without DoD investment, these technologies will not advance. These technologies will enable a *substantial increase in the exploitation of space* by the DoD. They will enable functions that are currently unaffordable or technically impossible.

- Evolutionary technologies in which the DoD should invest, because they are similarly critical to the military mission and have little or no commercial application. These technologies will enable gradual advances that over time can significantly improve the performance or reduce the life-cycle costs of military systems.

- Technologies in which little DoD investment is required, because they will be led by the commercial sector. In these areas, the DoD should carefully monitor the progress that industry is making and invest only to the level necessary to adapt commercial technologies to the military mission.

The DoD should not underestimate the benefits of a healthy synergism between military and commercial research and development.

The Air Force's investment in space technology has fallen in recent years both as a fraction of Total Obligation Authority (TOA) and as a fraction of spending on research and development. The inception of the Strategic Defense Initiative Organization (SDIO) in 1983 brought the primary Air Force space technology programs under the SDIO umbrella. During the heyday of SDIO, total DoD investment in space technology programs was more than $500M/year. The primary emphasis during this time was highly survivable space technology development and demonstration. In addition, major programs were initiated under the SDIO umbrella in active

and passive space sensors, radiation-hardened electronics, advanced high-data-rate communications, high-efficiency and high-power solar arrays, and high-density power storage technologies along with cryocoolers and other related structural technologies. Great emphasis was placed on technologies and systems that were highly survivable against a variety of threats including laser, nuclear, and microwave effects. The evolution of SDIO into the Ballistic Missile Defense Office (BMDO) and the subsequent program direction to address theater missile defense had a negative impact on the space technology development budget and, as a result, space technology investment has decreased from $500 M/year to $200M/year. This dramatic decrease in space technology development investments will have a serious impact on the dominant position of the US in space systems development, both commercial and military, for years to come.

Air Force investment in space technology is grossly inadequate. The current situation is similar to the state of affairs earlier in this century when the US lead in aircraft technology faltered and a sustained effort was required to recapture that lead. The exploitation of space for military advantage requires aggressive and continuous investment.

Space Technology and Space Systems in the Future

In the next ten to twenty years, the commercial world will see the development of four types of space-based systems that will be available to both friendly and unfriendly nations, corporations, and individuals on a worldwide basis. These systems will provide commercial services but will also be militarily useful. In addition, these systems will either involve other countries that build or purchase them or will involve international consortia of investors. These systems will lead to the growth of new service industries based around their use that will be economically powerful. (A current example is the Global Positioning System (GPS); the growth of civilian users, including the FAA, is now creating a dilemma about the compatibility of easy access to precision GPS with the DoD's need to maintain a competitive military advantage.)

Four types of commercial services that will be available are:

- Global positioning and navigation services. While the DoD already has GPS, other countries are developing equivalent systems or augmenting the existing one; similar capabilities will be available through the development of personal communication systems. They will enable navigation with an accuracy of at least several tens of meters.
- Global communication services. Several systems have already been proposed, such as Iridium, Globalstar, and Inmarsat-P. These systems will provide universal communications services between mobile individuals to almost any location on the surface of the Earth. These systems will work transparently with local cellular systems and will enable rapid telecommunications development in underdeveloped parts of the world.
- Information transfer services. These services will enable data transfer between any two points on the surface of the Earth at rates ranging from a few kilobits per second to gigabits per second. Proposed systems include Orbcomm, Spaceway, Cyberstar, and Teledesic. Individual users will be able to access large amounts of data on demand. Direct TV from direct broadcast satellites is a harbinger of what will be possible.

- Global reconnaissance services. These services will provide commercial users multispectral data on almost any point on the surface of the Earth with meter-scale resolution. This data will span the range from the radio frequencies (RF) to the infrared (IR) through the visible into the ultraviolet (UV). This information will be available within hours of a viewing opportunity and on the order of a day from the time of a request. Proposed systems include improvements to the French SPOT as well as Orbimage, World View, and various types of radar satellites.

Each of these services will be part of the global infosphere. It will be possible for persons of means to locate themselves on any point on the Earth, communicate both by voice and computer to other points on the Earth, and have a good picture of the local environment. Both the services and the technologies that enable them will be commercially available all over the world. Given the enormous magnitude of the commercial market, military and NASA communications will have to be fully integrated with and technologically dependent on the exploding market- driven communications technologies.

Nevertheless, there will be military-specific needs that are not encompassed by these four types of commercial services:

- Geographically selected denial of high-precision global positioning information (sufficient for weapons delivery) to an opponent, and assured friendly access to those same services
- Assured access to communications that are covert and/or robust against jamming and tampering, including local surge capacity to deployed forces
- Assured relay of very-high-data-rate intelligence information from geosynchronous distances
- Day/night all-weather reconnaissance of low-contrast stationary and moving targets with hyperspectral imaging and in the shortest possible time

The proliferation of space applications at affordable prices will tend to offset the current US military edge. Capabilities in these military-specific areas will enable the US military to have the advantage over an opponent who is also exploiting the infosphere.

Space Technology Developments in the Commercial World in the Next Twenty Years

To deliver the services described above in a competitive environment, the commercial world will invest in bringing many technologies relevant to space to commercial viability. The technologies that the commercial world will develop are:

- Technologies for manufacturing many identical spacecraft
- Technologies for efficient spacecraft operations
- Low-cost high-performance electronics and computers
- Technologies for commercial global communications
- Small expendable space launch systems

- Systems-level simulation-based design
- Technologies for automated spacecraft checkout

These technologies will result in standardized, modular bus designs that can be launched on any compatible launch vehicle, simplified payload designs, commoditized payload elements, and efficient (e.g., autonomous) operations. In addition, the commercial world will develop management techniques to reduce system cost and delivery time as well as refining techniques for cost estimating and scheduling. Relying on the commercial world to develop these technologies, the Air Force will need to invest only where it is necessary to adapt these technologies to meet specific military requirements.

However, not all of the functions needed by the Air Force will be achievable solely with commercial developments.

Implications of the Vision for the Air Force in Space

The vision for the Air Force in space requires increased capability over projected commercial systems, yet these increases will need to come in a time of decreasing budgets. Therefore, the cost of space systems must be reduced to make these capabilities achievable. The costs of space systems are dominated by the costs of the individual elements, the costs to launch the space elements, and costs to operate them. Historically, the cost of space hardware has scaled directly with mass. To break the current cost paradigm in each of these areas it is necessary to invest in or to invest to adapt from the commercial world several key technologies. The relevant technologies are those that reduce the satellite mass for the same or increased functionality, technologies for launch vehicle cost reductions and performance improvement, and technologies for spacecraft automation.

Four Achievable Themes that Will Constitute the Vision for Space

With the attribute of affordable systems as an overarching consideration, space technology investments can be grouped under the four themes of Global Awareness, Knowledge on Demand, Space Control, and Force Application. These themes will be enabled by targeted investments by the DoD as well as related investments in the commercial sector.

Global Awareness

Global Awareness is the idea that space technology will enable the ability to see in near real time everywhere on the surface of the Earth or in the air or near space, under all weather conditions, at any time. The integration of this ability with the command and control system for a military operation will enable the US military to respond and out think any potential adversary in a context where space-based information will be available on a world wide basis. The timely acquisition and use of information will confer a tremendous advantage on US forces. Global Awareness also has enormous deterrent value. Any adversaries will know that they are under continuous surveillance by active and passive means at all times, under all conditions.

Global Awareness will be powerfully enabled by Air Force investment in technologies that will make possible large sparse apertures, evolving in the direction of clusters of cooperating satellites. Such clusters will enable aperture sizes that are bigger than those now only available

with large satellites. In addition, constellations of large numbers of smaller satellites will allow economy of scale in production and will have reduced vulnerability relative to single satellites. Also important to Global Awareness are the technologies for space-based active probing such as synthetic aperture radar (for day/night all-weather coverage) as well as technologies for passive probing through hyper- and ultraspectral sensors. These capabilities will enable any point on the surface of the Earth or the air to be scanned in over a wide range of electromagnetic bands.

Knowledge on Demand

Knowledge on demand is the idea that an individual warfighter could request knowledge about some area of operations. The warfighter has always benefited from having strong situational awareness in which he or she is called upon to fight. The human mind is very capable of assessing patterns in information and using those patterns to make decisions. As the infosphere envisioned by the commercial world develops, there will be a plethora of information available at many levels to US warfighters. Indeed, there will be so much information to collect, analyze, assess, synthesize and disseminate that the quantity will be overwhelming. What the warfighter needs is not information, but knowledge. Knowledge will come from a fusion of information from all types of sensor sources (air, ground, and sea as well as space) together with communications to deliver knowledge to the user.

The warfighter could request to see all the new threats in an area or an update on old threats or new targets. That request would be entered into a global integrated information system and if appropriate, a space-based set of sensors would provide the knowledge. The communication would be direct to the system, the request would be processed by the system, the data would be collected by the system, the knowledge would be extracted from the information gathered by the system, and that knowledge would be sent to the warfighter. This use of space-, air-, sea-, and ground-based assets combined with Global Awareness will enable direct and timely readout to tactical users. This integrated use of space-based assets is one of the aspects of information dominance and information warfare. The technologies that will enable Knowledge on Demand are the technologies of image processing, secure high-data-rate anti-jam communications, data fusion, artificial intelligence, neural networks, and distributed processing.

Space Control

The value of space systems and the advantages that they will give to the US will be so large that an adversary would be foolish not to target those space assets. In the next several years, the technology to selectively target an individual satellite will have proliferated all over the world and will be available to anyone at a relatively modest cost. Space systems can be targeted by a determined adversary with electronic warfare, high-power microwaves, lasers, and, as ballistic missile technology proliferates, with collateral nuclear weapons and kinetic-kill vehicles. The use of these degradation mechanisms can be made precise enough to allow a whole range of options ranging from temporary blinding of a sensor to permanent destruction of a sensor to physical destruction of a satellite. With this range of technology available in the world, it is important that the Air Force invest in the technologies for Space Control in a hostile environment. These technologies will allow US systems to survive and function in the kind of hostile environment that almost any adversary will be able to create in the future. The

distributed satellite systems necessary for Global Awareness and Knowledge on Demand will be inherently survivable since functions will be spread among many satellites.

Space Control can be divided into three technology areas: space asset surveillance, space asset negation, and space asset protection. It is important to know what assets are in space, to determine what capabilities they have, and to be able to distinguish them from background chaff and debris. The technologies that will enable effective space asset surveillance are sensor technologies. Once assets are identified, it may be necessary to undertake negation of an adversary's assets using directed energy, kinetic kill vehicles, or information warfare. The technologies that will enable space-based asset degradation are autonomy technologies that will enable a smart interceptor to be released from carrier spacecraft and then accomplish a mission to degrade a specific satellite without requiring ground control. However, it is also important to increase the survivability of friendly satellites. Space asset protection is necessary against both natural threats such as orbital debris and radiation as well as human-generated threats. Threats can be handled by making satellites hard to find, hard to track, and then hard to damage or kill. The technologies to substantially enhance survivability are low observable technologies and maneuvering technologies (which require high power). Space-based directed energy weapons for the protection of space assets will be enabled by the technologies of high power generation in space.

Force Application

The application of force from space to ground or air will be feasible and affordable in the next twenty to thirty years. Force Application by kinetic kill weapons will enable pinpoint strikes on targets anywhere in the world. Such force projection will enable Global Awareness to extend to global presence. The current Air Force mission area of Force Application includes both nuclear and conventional deterrents to place an adversary's terrestrial targets at risk. The technology for precision kinetic energy strike of fixed terrestrial targets from space-based or ballistic missile platforms is available to the US now. Technologies such as microelectromechanical systems (MEMS) could substantially improve the affordability of such systems. Technologies for similar conventional strike of mobile targets are possible given the appropriate targeting and command and control. Discussion of this kind of capability has so far focused on very limited capacity for a narrow range of targets. However, the technology suggests the possibility of a dramatic change in the means available for global power projection, making logistic delay negligible and recovering the investment in energy for logistic deployment directly as destructive energy on targets. The equivalent of the Desert Storm strategic air campaign against Iraqi infrastructure would be possible to complete in minutes to hours essentially on immediate notice. Force application by means of directed energy weapons will be feasible if the Air Force invests in the technologies for large amounts of power generation and energy storage. The technologies to enable this application will not be developed by the commercial sector and must be developed by the Air Force.

US perspectives on this kind of capability are colored by past investment in conventional force projection and by Cold War attitudes about deterrence. The use of ballistic missile platforms for conventional strike raises an ambiguity in nuclear deterrence that would have been destabilizing in the bipolar Cold War context. Use of orbital platforms for conventional strike

raises a similar ambiguity regarding verification of the treaty banning weapons of mass destruction in space. The opportunity for others to exploit this avenue to global power will be readily accessible to the large community of nations achieving access to space. Awareness of this opportunity should help motivate Air Force investments in Force Application and missile defense.

Recommendations for Investment in Space Technology

A combination of targeted Air Force investment and adaptation of commercial development will enable a revolutionary change in Air Force space capability. Such change in the next twenty years will be *affordable* and based around *Global Awareness, Knowledge on Demand, Space Control* and *Force Application.* Air Force technology investment must be carefully directed to provide the greatest return.

Revolutionary Technologies in Which the Air Force Must Invest

Several key technologies offer the possibility of a substantial increase in the exploitation of space by the Air Force, the potential impact of which is so great that the Air Force must invest now. The first three of these technologies will enable much larger payload fractions to be lifted to orbit by factors of four or more and, combined with affordable operations, will enable much cheaper access to orbit. Therefore they have the potential to revolutionize the launch equation and remove the significant barrier that high launch costs impose. These technologies are:

- High-energy-density chemical propellants to enable spacelift with high payload mass fractions—specific impulses of 1000 seconds or greater (in high-thrust systems) should be the goal of this effort
- Lightweight integrated structures combining reusable cryogenic storage, thermal protection, and self diagnostics to enable a *responsive* reusable launch capability
- High-temperature materials for engines and rugged thermal protection systems

The next two technologies will enable space-based weapons such as high power lasers, space-based radars with wide search areas, and satellites that can maneuver almost at will. They have the potential to substantially remove orbital dynamics as a barrier to where satellites can go. These technologies are:

- High performance maneuvering technologies such as electric propulsion (with thrusts greater than tens of Newtons, at specific impulses of thousands of seconds at near 100% efficiency, the goal for electric propulsion) and tethers for momentum exchange
- Technologies for high power generation (greater than 100 kiloWatts) such as nuclear power, laser power beaming, and electrodynamic tethers

The final set of technologies will enable a new vision for space applications where functionality is spread over many satellites rather than only in a single satellite. They have the potential to enable new applications from space (such as Global Awareness) at affordable cost. These technologies are:

- Technologies for clusters of cooperating satellites (e.g., high-precision stationkeeping, autonomous satellite operations, and signal processing for sparse apertures)

Evolutionary Technologies in Which the Air Force Should Invest

The Air Force should invest for evolutionary improvements in performance or reduced life-cycle costs to its systems. The technologies that offer such benefits are:

- Launch vehicle technologies
  - Engines, upper stages, and solar thermal propulsion
  - Vehicle structures (e.g., aluminum-lithium (Al/Li) or advanced composite tankage, as well as multifunctional structures)
- Satellite bus technologies
  - Structure technologies (e.g., lightweight structures, active vibration suppression, precision deployable structures, and software-controlled multifunctional surfaces)
  - Innovative energy storage technologies (e.g., the electromagnetic flywheel battery)
  - Attitude control technologies, including attitude sensors and attitude control system (ACS) algorithms
  - Radiation hardening technologies for spacecraft electronics
  - Low-observable technologies
  - Microelectromechanical systems (MEMS) technologies
- Sensor technologies
  - Large, sensitive focal plane arrays and associated readout and cooler technologies for hyper- and ultraspectral sensing of small low-contrast targets and long-wavelength detection against the cold background of space
  - Active sensor technologies (e.g., large lightweight antennas, high-efficiency radio frequency (RF) sources for synthetic aperture radar (SAR) and moving target indicator (MTI) radar, and high-energy lasers for lidar)
  - MEMS (including on-chip optics)
- Communications technologies
  - Very high-rate, long-distance optical communications
  - Multi-beam adaptive nulling antennas for anti-jam communications
- Data fusion technologies, including automatic target recognition
- Space-based weapons technologies

- Laser weapons technologies (e.g., large lightweight optics)
- Technologies for smart interceptors (e.g., autonomous guidance, MEMS)
- RF weapons technologies (e.g., lightweight energy storage) for electromagnetic pulse (EMP) and jamming

Commercially Led Technologies

Another set of technologies that will allow for evolutionary change in Air Force space operations will be driven by the commercial sector. These technologies merit minimal investment by the Air Force, yet the Air Force should invest as necessary to adapt these technologies to its needs. These technologies are:

- Small launch vehicles
- High-efficiency energy conversion and storage
- High-data-rate RF communications
- Technologies for debris reduction
- Information storage, retrieval, and processing technologies and protocols
- Image processing, coding, compression, and very large scale integration (VLSI) architectures
- Neural networks and artificial intelligence
- Technologies for spacecraft manufacturing
- Technologies for vehicle and spacecraft operations

Recommendations for Management Improvements

Space technology development occurs currently under NASA, DoD, NRO, DoE, and industry auspices. Execution of the resulting programs is only loosely coordinated through teaming, informal communication between investigators, professional society fora, and ad hoc topical organizations. Planning of the technology investment and programs by the various agencies is largely independent and uncoordinated. To create an efficient, coherent national space technology strategy, the Air Force should take the lead in establishing collaborative planning, advocating appropriate changes to US Space Policy, and encouraging coordinated execution of space technology development among all these organizations.

The chance to exploit commercial lead in some space technologies presents the opportunity for reduced government technology investment, reduced cycle time, and lower cost space systems. The ability to reap those benefits requires the discipline to accept the constraints of commercial capability in acquisition and in technology investment.

The recommended revolutionary and evolutionary technologies will provide the greatest benefit to the Air Force in the future and will not be developed by the commercial and civil communities. The least expensive route to meet future needs in space is a sustained government investment and continuity of effort.

Conclusions

The Space Technology Panel has determined:

- The international exploitation of space services will grow
- The Air Force will be able to take advantage of complementary commercial investment
- There are revolutionary technologies that will enable a new vision for the Air Force in space
- To effectively support the warfighter from space, active and sustained investment in these revolutionary technologies is essential

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1.0 Introduction

1.1 Vision

The Space Technology Panel's recommendations for technology investments derive from a vision of the Air Force in space in the 21st century, in which the Air Force has achieved *survivable, on demand, real time, global presence that is affordable.* This vision represents a *revolutionary* increase in capabilities for the Air Force and is achievable with targeted Air Force technology investments and adaptation of commercial developments. These technology investments will enable the US to maintain military superiority by the exploitation of space through four themes:

- Global Awareness
- Knowledge on Demand
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1.2 Background

This report is a part of the Scientific Advisory Board's (SAB's) response to the challenge by Secretary of the Air Force Sheila Widnall and the Air Force Chief of Staff General Ronald Fogleman to "search for the most advanced air and space ideas and project them into the future."[2]

This report identifies the space technology investment areas for the Air Force that will provide substantial and affordable improvements to USAF space capabilities over the next 10-30 years. The Secretary and the Chief of Staff levied this challenge because of the "blistering" pace of technological change and the need to adapt swiftly to new developments. Specifically, the *New World Vistas* participants were challenged to:

- Provide a ten year technological forecast
- Predict how the explosive rate of technological change will impact the Air Force over the next ten years
- Identify fields of rapidly changing technology and assess their impact on the modern Air Force
- Identify those areas which will most likely revolutionize the 21st century Air Force
- Predict the impact of these technological changes on affordability of Air Force weapons systems and operations
- Predict Science and Technology (S&T) areas where the Air Force can minimize its investment and turn to the commercial world for technology development

2. Letter from SECAF Widnall and CSAF Fogleman to Dr. Gene McCall, New World Vistas Challenge for Scientific Board (SAB), 29 November 1994

- Highlight opportunities for dual use, possibilities for defense conversion, and mechanisms for capitalizing on technology advancement in the commercial sector
- Identify areas where the Air Force can rely on, or partner with, commercial industry for technology development
- Identify the areas where the Air Force is not the innovator, but a large high tech customer—offer advice on how the Air Force can be a better customer
- Predict S&T areas that the Air Force will have to develop, where no commercial market exists or will likely develop—highlight related industrial base issues
- Offer advice as to whether the Air Force lab structure is consistent with these new vistas and what changes, if any should be made
- Offer advice as to whether the current SAB charter is consistent with those new vistas, and what changes if any, should be made
- Evaluate proposals in light of how the Air Force contributes to the joint team[3]

Twelve panels were formed to respond to Air Force leadership's tasking. These panels were: Aircraft and Propulsion, Attack, Directed Energy, Human Systems/Biotechnology, Information Applications, Information Technology, Materials, Mobility, Munitions, Sensors, Space Applications, and Space Technology.

In light of the Secretary's and Chief of Staff's challenge, the Space Technology Panel developed a specific charter to guide and focus its efforts, and determined to:

- Identify new technologies for space applications in a 10-30 year timeframe that will offer
  - Fundamental improvements in Air Force capabilities
  - Significantly lower life cycle costs for future capabilities
- Consider the impact of commercial or dual-use technologies for space for the future and identify the technology path for incorporation into Air Force systems
- Seek out technologies that may lead to new paradigms in space applications

1.3 Assumptions

The recommendations contained in this report rest on the following key assumptions:

- Many nations and industries will be active and competitive in space
- Increasing reliance on space systems for military functions will add a new dimension to the vulnerability of US space systems and operations
- Although the commercial sector will lead in certain areas of technology driven by consumer demand, it will not lead in other sectors of military technology

3. Letter from SECAF Widnall and CSAF Fogleman to Dr Gene McCall, New World Vistas Challenge for Scientific Advisory Board (SAB), 29 November 1994

- Current understanding of the laws of physics must bound any recommendations for technology investment

1.4 The Current Situation in Space

Space will continue to be the proverbial high ground for the foreseeable future. Operation Desert Storm showed that space assets integrated with air, ground, and sea assets can play a critical role as force enhancers in fighting and winning conflict. Senior Air Force leadership[4] asserts that "space systems signal America's stature as a world power and aerospace nation. Control of space and access to it are fundamental to economic and military security. Ask the 20 foreign countries who will have space capabilities by the year 2000: a presence in space implies influence, power and security."

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The reduction of resources available to the DoD in the post-Cold War era means that DoD investment in space technologies and space systems must be firmly rooted in the goal of affordable systems. To this end, the DoD must plan its technology investment with a clear view of technological advances in the commercial world. It is undesirable and unnecessary for the DoD to develop every technology for its space systems on its own. There are many technologies that the commercial sector will develop that the military can adapt for its use with minimal investment. On the other hand, there will always be unique requirements for military systems that necessitate the use of technologies that have no commercial application, that push the performance limits of dual-use technologies, or whose timescale and risk are not attractive to thecommercial sector. The DoD should carefully target its investments in technology to achieve the highest possible return. Technologies that are candidates for DoD investments fall into one of three possible categories:

4. Hon. Sheila E. Widnall, Secretary of the Air Force, September 1993

- Revolutionary technologies in which the DoD must invest vigorously, because they are critical to the military mission and have little or no application in the commercial sector; without DoD investment, these technologies will not advance. These technologies will enable a *substantial increase in the exploitation of space* by the DoD. They will enable functions that are currently unaffordable or technically impossible.
- Evolutionary technologies in which the DoD should invest, because they are similarly critical to the military mission and have little or no commercial application. These technologies will enable gradual advances that over time can significantly improve the performance or reduce the life-cycle costs of military systems.
- Technologies in which little DoD investment is required, because they will be led by the commercial sector. In these areas, the DoD should carefully monitor the progress that industry is making and invest only to the level necessary to adapt commercial technologies to the military mission.

The DoD should not underestimate the benefits of a healthy synergism between military and commercial research and development.

The Air Force's investment in space technology has fallen in recent years both as a fraction of Total Obligation Authority (TOA) and as a fraction of spending on research and development. The inception of the Strategic Defense Initiative Office (SDIO) in 1983 brought the primary Air Force space technology programs under the SDIO umbrella. During the heyday of SDIO, total DoD investment in space technology programs was more than $500M/year. The primary emphasis during this time was highly survivable space technology development and demonstration. In addition, major programs were initiated under the SDIO umbrella in active and passive space sensors, radiation-hardened electronics, advanced high-data-rate communications, high-efficiency and high-power solar arrays, and high-density power storage technologies along with cryocoolers and other related structural technologies. Great emphasis was placed on technologies and systems that were highly survivable against a variety of threats including laser, nuclear, and microwave effects. The evolution of SDIO into the Ballistic Missile Defense Office (BMDO) and the subsequent program direction to address theater missile defense had a negative impact on the space technology development budget and, as a result, space technology investment has decreased from $500 M/year to $200M/year. This dramatic decrease in space technology development investments will have a serious impact on the dominant position of the US in space systems development, both commercial and military, for years to come.

Air Force investment in space technology is grossly inadequate. The current situation is similar to the state of affairs earlier in this century when the US lead in aircraft technology faltered and a sustained effort was required to recapture that lead. The exploitation of space for military advantage requires aggressive and continuous investment.

1.5 Space Technology and Space Systems in the Future

In the next ten to twenty years, the commercial world will see the development of four types of space-based systems that will be available to both friendly and unfriendly nations,

corporations, and individuals on a worldwide basis. These systems will provide commercial services but will also be militarily useful. In addition, these systems will either involve other countries that build or purchase them or will involve international consortia of investors. These systems will lead to the growth of new service industries based around their use that will be economically powerful. (A current example is the Global Positioning System (GPS); the growth of civilian users, including the FAA, is now creating a dilemma about the compatibility of easy access to precision GPS with the DoD's need to maintain a competitive military advantage.)

Four types of commercial services that will be available are:

- Global positioning and navigation services. While the DoD already has GPS, other countries are developing equivalent systems or augmenting the existing one; similar capabilities will be available through the development of personal communication systems. They will enable navigation with an accuracy at least several tens of meters.

- Global communication services. Several systems have already been proposed, such as Iridium, Globalstar, and Inmarsat-P. These systems will provide universal communications services between mobile individuals to almost any location on the surface of the Earth. These systems will work transparently with local cellular systems and will enable rapid telecommunications development in underdeveloped parts of the world.

- Information transfer services. These services will enable data transfer between any two points on the surface of the Earth at rates ranging from a few kilobits per second to gigabits per second. Proposed systems include Orbcomm, Spaceway, Cyberstar, and Teledesic. Individual users will be able to access large amounts of data on demand. Direct TV from direct broadcast satellites is a harbinger of what will be possible.

- Global reconnaissance services. These services will provide commercial users multispectral data on almost any point on the surface of the Earth with meter-scale resolution. This data will span the range from the radio frequencies (RF) to the infrared (IR) through the visible into the ultraviolet (UV). This information will be available within hours of a viewing opportunity and on the order of a day from the time of a request. Proposed systems include improvements to the French SPOT as well as Orbimage, World View, and various types of radar satellites.

Each of these services will be part of the global infosphere. It will be possible for persons of means to locate themselves on any point on the Earth, communicate both by voice and computer to other points on the Earth, and have a good picture of the local environment. Both the services and the technologies that enable them will be commercially available all over the world. Given the enormous magnitude of the commercial market, military and NASA communications will have to be fully integrated with and technologically dependent on the exploding market- driven communications technologies.

Nevertheless, there will be military-specific needs that are not encompassed by these four types of commercial services:

- Geographically selected denial of high-precision global positioning information (sufficient for weapons delivery) to an opponent, and assured friendly access to those same services;
- Assured access to communications that are robust against jamming and tampering and/or covert, including local surge capacity to deployed forces;
- Assured relay of very-high-data-rate intelligence information from geosynchronous distances;
- Day/night all-weather reconnaissance of low-contrast stationary and moving targets with hyperspectral imaging and in the shortest possible time;

The proliferation of space applications at affordable prices will tend to offset the current US military edge. Capabilities in these military-specific areas will enable the US military to have the advantage over an opponent who is also exploiting the infosphere.

1.6 Space Technology Developments in the Commercial World in the Next Twenty Years

To deliver the services described above in a competitive environment, the commercial world will invest in bringing many technologies relevant to space to commercial viability. The technologies that the commercial world will develop are:

- Technologies for manufacturing many identical spacecraft
- Technologies for efficient spacecraft operations
- Low-cost high-performance electronics and computers
- Technologies for commercial global communications
- Small expendable space launch systems
- Systems-level simulation-based design
- Technologies for automated spacecraft checkout

These technologies will result in standardized, modular bus designs that can be launched on any compatible launch vehicle, simplified payload designs, commoditized payload elements, and efficient (e.g.,autonomous) operations. In addition, the commercial world will develop management techniques to reduce system cost and delivery time as well as refining techniques for cost estimating and scheduling. Relying on the commercial world to develop these technologies, the Air Force will need to invest only where it is necessary to adapt these technologies to meet specific military requirements.

However, not all of the functions needed by the Air Force will be achievable solely with commercial developments.

1.7 Implications of the Vision for the Air Force in Space

The vision for the Air Force in space requires increased capability over projected commercial systems, yet these increases will need to come in a time of decreasing budgets. Therefore,

the cost of space systems must be reduced to make these capabilities achievable. The costs of space systems are dominated by the costs of the individual elements, the costs to launch the space elements, and costs to operate them. Historically, the cost of space hardware has scaled directly with mass. To break the current cost paradigm in each of these areas it is necessary to invest in or to invest to adapt from the commercial world several key technologies. The relevant technologies are those that reduce the satellite mass for the same or increased functionality, technologies for launch vehicle cost reductions and performance improvement, and technologies for spacecraft automation.

With the attribute of affordable systems as an overarching consideration, space technology investments can be grouped under the four themes of Global Awareness, Knowledge on Demand, Space Control, and Force Application. These themes will be enabled by targeted investments by the DoD as well as related investments in the commercial sector.

1.7.1 Global Awareness

Global Awareness is the idea that space technology will enable the ability to see in real time everywhere on the surface of the Earth or in the air or near space, under all weather conditions, at any time. The integration of this ability with the command and control system for a military operation will enable the US military to respond and outthink any potential adversary in a context where space-based information will be available on a worldwide basis. The timely acquisition and use of information will confer a tremendous advantage on US forces. Global Awareness also has enormous deterrent value. Any adversaries will know that they are under continuous surveillance by active and passive means at all times, under all conditions.

Global Awareness will be powerfully enabled by Air Force investment in technologies that will make possible large sparse apertures, evolving in the direction of clusters of cooperating satellites. Such systems will enable aperture sizes that are bigger than those now only available with large satellites. In addition, the large number of smaller satellites involved will allow economy of scale in production and will have reduced vulnerability relative to single satellites. Also important to Global Awareness are the technologies for space-based active probing such as synthetic aperture radar, as well as technologies for passive probing through hyper- and ultraspectral sensors. These capabilities will enable any point on the surface of the Earth or the air to be scanned over a wide range of electromagnetic bands.

1.7.2 Knowledge on Demand

Knowledge on demand is the idea that an individual warfighter could request knowledge about some area that he or she is about to enter. The warfighter has always benefited from having strong situational awareness in which he or she is called upon to fight. The human mind is very capable of assessing patterns in information and using those patterns to make decisions. As the infosphere envisioned by the commercial world develops, there will be a plethora of information available at many levels to warfighters. Indeed, there will be so much information to collect, analyze, assess, synthesize, and disseminate that the quantity will be overwhelming. What the warfighter needs is not information, but knowledge. Knowledge will come from a fusion of information from all types of sensor sources (air, ground, and sea as well as space) together with communications to deliver knowledge to the user.

The warfighter could request to see all the new threats in an area or an update on old threats or new targets. That request would be entered into a global integrated information system and if appropriate, a space-based set of sensors would provide the knowledge. The communication would be direct to the system, the request would be processed by the system, the data would be collected by the system, the knowledge would be extracted from the information gathered by the system, and that knowledge would be sent to the warfighter. This use of space-, air-, sea, and ground-based assets combined with Global Awareness will enable direct and timely readout to tactical users. This integrated use of space-based assets is one of the aspects of information dominance and information warfare. The technologies that will enable Knowledge on Demand are the technologies of image processing, secure high-data-rate anti-jam communications, data fusion, artificial intelligence, neural networks, and distributed processing.

1.7.3 Space Control

Desert Storm demonstrated to the world the value of space for warfighting, and historically, the US has operated in space without hindrance. Consequently, US military space forces have evolved into high-value, highly visible, vulnerable targets. As one senior officer said, "We are now in a target-rich environment." The US is not prepared to protect these assets from a Pearl Harbor-type attack. Such an attack could significantly affect the effectiveness of US forces as they become increasingly dependent of space assets.

Control of the battlespace is a key enabling priority for the warfighter. As warfighting has moved from ground to sea to air and now to space, control of each new medium has brought new challenges.

Control of the space medium is similar to the others in that it requires freedom of action in accomplishing objectives (whether they be military, civil, or commercial) while denying similar freedom of action to potential adversaries. While the objectives among the media are similar, the means to accomplish Space Control differ due to the peculiar characteristics of space.

The Space Control mission has three aspects:

- Surveillance
- Protection
- Counter-force operations

The mission of space surveillance is to determine the space order of battle and the background environment. The protection aspect includes all actions required to assure the availability of US space forces, including identifying threats, commanding responses, and designing in capabilities for survivability. The counterforce mission is to disrupt, degrade, deny, or destroy (as appropriate) the space, ground, or command and control segments of the space systems available to an adversary.

Current capabilities to support Space Control are fragmented and do not permit the exercise and training with joint warfighters needed to develop doctrine and tactics. Consequently, the ability to assess the military impact of any offensive counterspace actions is extremely limited. Similar uncertainties exist for defensive counterspace activities. For example, while it may be

clear when a radio-frequency interference (RFI) event is a problem for a satellite, characterizing the nature of the interference as hostile is usually impossible with today's technology. Without having confirmation that hostile intent is involved, the RFI instance is usually ascribed to benign sources. It is important that this environment of ambiguity be removed.

The first step in control of the space environment is to develop a comprehensive understanding of what exists in that environment. With the proliferation of nations fielding (or purchasing through commercial arrangements) ever more capable space systems that can be used for military purposes, more extensive effort will be required to characterize the space capabilities of potential adversaries. This must include characterization, not only of systems owned and operated by potential adversaries, but those available through commercial means. Regular surveillance of space to maintain orbital element sets for satellites of interest and to characterize these systems (mission payload assessment or MPA) will be required. Detailed intelligence support will also be necessary to identify the ground segments and other supporting elements of space systems.

As space systems mature, additional challenges to surveillance are arising in keeping track of maneuvering payloads, characterizing smaller size payloads, and coping with the increasing number of payloads in geosynchronous orbit. Current dependence today on a ground-based space surveillance network, with geographic limitations and concerns about annual operating costs, creates severe limitations on the US ability to closely monitor maneuvering payloads. The increasing catalog of active payloads also poses challenges in MPA. Ground sensors are hampered by constraints imposed by viewing geometry, weather, and time of day, requiring a proliferation of sites which is becoming cost-prohibitive. A cost-effective solution to timely maneuver detection, battle damage assessment (BDA), and (perhaps) MPA would be to accomplish this surveillance from space, where a smaller number of sensors could collect more information.

Technologies driven by a space-based solution include: scheduling and tasking algorithms to integrate space assets; autonomous search, detect and track algorithms for space-based sensors, and key technologies to operate these sensors in space environments such as long-life cryogenic coolers and contamination control. Other enhancements include onboard processing and data fusion, as well as low-mass, lightweight and large-aperture optics.

Other, perhaps interim, solutions to stretch the capabilities of existing sites could also aid in the responsiveness of space surveillance. Active laser illumination of satellites of interest supports 24-hour and deep-space collection. Current efforts on the active imaging testbed support this technology. This testbed environment, at Starfire Optical Range, is tackling the technical issues associated with the illumination of a satellite by a laser (beam control, propagation, etc.) which will allow tracking and imaging during hours of darkness.

Detailed satellite of interest characterization is required for development of the space order of battle. Collection of multi-phenomenology data will aid in the MPA process with the resulting information then fused and stored in interactive databases to support threat analysis and targeting. Efforts in hyperspectral imaging, optical interferometry, and signature data exploitation techniques support these needs.

To protect space systems, the segments must be hard to find, hard to track, hard to discriminate, and hard to damage or kill. The key first steps in protecting space systems come from continual monitoring of potential threats and early warning when a friendly satellite is receiving increased interest by potential adversaries. At a minimum, it will be necessary to detect when friendly satellites receive increase scrutiny by active tracking. Recent successful operations of the Technology for Autonomous Operational Survivability (TAOS) satellite have aided in this understanding. Small, lightweight, low-power packages capable of detecting and geolocating a wide variety of threats are within current technology. Further miniaturization will facilitate integrating these receivers on a broader array of space assets.

Key protection technologies include: low observability, maneuverability, shielding, self-sensing and self-healing systems, and proliferated or distributed architectures.

The protection of the ground and command and control segment of space systems is also vital. Security countermeasures such as intrusion detection, access control, and proliferation are typically used. As the consolidation of ground elements is being pursued, a careful nodal analysis that examines the vulnerabilities of US systems must be performed to ensure that adequate protection is maintained. Increased spacecraft autonomy will minimize the need for contact with the ground and thereby reduce vulnerability.

Counterspace negation options must evaluate all segments of the space system and its supporting infrastructure. Existing capabilities are predominantly focused on ground and command and control segments. In the space segment, classic efforts in satellite negation have focused on kinetic-kill and directed energy applications for disruption, denial, degradation, and destruction. Technologies in these areas are at a sufficient maturity level to initiate a program. Other emerging technologies, specifically, high power microwave capabilities and techniques tied to information warfare, could be brought to bear in this area.

As civil and commercial space capabilities in the areas of navigation, communications, weather, and remote sensing increase in number and capability, more attention must be paid to preserving US advantage while adversaries use these systems for military purposes. Denial of GPS data is a classic example of this.

Future US Space Control capabilities must allow for true control of the space environment with the same surety as other mediums. The picture of the space environment must be complete to include a detailed understanding of all on-orbit systems an adversary could exploit (military, civil, and commercial) and all capabilities used to support friendly military forces. This detailed picture supports the development of options for Space Control protection, prevention, and negation. Space Control capabilities must be available to allow engagement of all space capabilities available to potential adversaries. Key US space systems must be hardened to withstand or avoid attacks. Space systems and data must be controlled to prevent adversary access to either the space-derived information or the space asset itself. This prevention must be accomplished while still allowing US/Allied warfighters access to the data. Adversary access to space must be negated by identification of the key vulnerable nodes and denial or elimination of the node. Key to the success of these options will be a timely assessment of their effectiveness supporting re-targeting for ultimate control of space.

1.7.4 Force Application

The current Air Force mission area of Force Application includes both nuclear and conventional deterrents to place adversary terrestrial targets at risk. The technology for precision kinetic energy strike of fixed terrestrial targets from space-based or ballistic missile platforms is available to the US now. Technologies such as microelectromechanical systems (MEMS) could substantially improve the affordability of such systems. Technologies for similar conventional strike of mobile targets are possible given the appropriate targeting and command and control. Discussion of this kind of capability has so far focused on a very limited capacity for a narrow range of targets. However, the technology suggests the possibility of a dramatic change in the means available for global power projection, making logistic delay negligible and recovering the investment in energy for logistic deployment directly as destructive energy on targets. The equivalent of the Desert Storm strategic air campaign against Iraqi infrastructure would be possible to complete in minutes to hours essentially on immediate notice.

US perspectives on this kind of capability are colored by past investment in conventional force projection and by cold war attitudes about deterrence. The use of ballistic missile platforms for conventional strike raises an ambiguity in nuclear deterrence that would have been destabilizing in the bipolar cold war context. Use of orbital platforms for conventional strike raises a similar ambiguity regarding verification of the treaty banning weapons of mass destruction in space. The opportunity for others to exploit this avenue to global power will be readily accessible to the large community of nations achieving access to space. Awareness of this opportunity should help motivate Air Force investments in Force Application and missile defense.

1.8 Report Organization

The remainder of this report covers specific space technology areas. Chapter 2 discusses space launch technologies, including both expendable and reusable launch vehicles. Chapter 3 reviews spacecraft bus technologies such as power, propulsion, structures, and other subsystems that are common to all space assets. Chapter 4 discusses spacecraft payload technologies, including sensors, communication systems, and onboard processing. Chapter 5 discusses spacecraft manufacturing, operations, and software as issues that cut across the launch, bus, and payload areas. Finally, Chapter 6 contains a summary of the Space Technology Panel's conclusions and recommendations.

Within each technology area, the report identifies specific technologies for revolutionary change in which the Air Force must invest, technologies for evolutionary change in which the Air Force should invest, and technologies that will be led by the commercial sector in which the Air Force should invest to adapt.

Appendices A through C describe the charter of the Space Technology Panel, provide information on the panel members, and list the meetings the panel held. Appendix D is a compilation of the acronyms used in this report. Appendix E summarizes other relevant reports on space technology, while Appendices F and G list the white papers and briefings that the panel received during the *New World Vistas* study.

2.0 Launch Vehicle Technologies

2.1 Introduction

The future launch requirements for the Air Force and the nation and the technologies needed to meet these requirements have been studied extensively in the recent past. Virtually every study over the past twenty years has highlighted the need to lower the cost of access to space. Launch costs of existing expendable launch vehicles—most of which in the US are based on designs originally produced as ballistic missiles—are a major factor in space systems affordability and have historically been an inhibiting influence on the nation's approach to exploiting space. Despite the early cost-reduction projections of NASA's "reusable" Space Transportation System (STS), little progress has been made over the past two decades in significantly lowering the cost of access to space. All of the world's existing market economy launchers (from small expendable rockets to the STS) place payloads in low earth orbit (LEO) for between \$8,000 and \$16,000 per pound. The cost of placing satellites in geostationary orbit (GEO) is even more daunting: approximately \$30,000 per pound. The high cost of launch is pervasive in its effect. Within the national security space community, launch costs have contributed to a paradigm that embodies several dilemmas:

- Satellites have tended to become heavier in order to perform their intended function and survive in the harsh space environment for as long as possible.
- Long-lived satellites mean fewer launches, so economies of scale are elusive and satellites become technologically antiquated early in their mission life.
- Big, long-lived, complex satellites are enormously expensive, typically costing \$40,000 per pound (or more) to produce.
- The cost of launch failure with such expensive satellites is almost prohibitive, resulting in a strongly risk-averse mentality.
- Existing launch systems all have high reliability (0.92 - 0.99) because reliability and performance have historically had a greater emphasis than cost.
- Until lower cost launchers demonstrate equally high reliability, satellite program offices will not entrust their payloads to new launchers.
- Without sufficient assurance of payload customers, it is difficult to secure the capital required to commercially develop launchers and to demonstrate the needed reliabilities.

These statements describe the strong cause-and-effect relationship between the spacelift function and on-orbit capability. The current environment has an impact not just in the development and operational communities, but in the technology community as well. Technologies that violate this paradigm, but offer other advantages, have not always been well received. Several factors have emerged over the past several years that are prompting changes in the environment:

- Foreign competition, offering lower-cost systems, has captured more than half the free world's annual commercial launch market.

- The US federal budget is under severe pressure to reduce chronic deficits.
- Decision makers realize that exploiting the full potential of space will require less expensive ways of achieving orbit.
- Technologies are emerging that allow much smaller satellites to be produced, while still meeting mission needs.

Over the past ten years, the Air Force has embarked on several attempts to develop a new space launch system, some of them in cooperation with NASA. Each attempt has failed because of a lack of consensus on the requirements, and because the cost of a new launcher development (estimated at $10B or more) was assessed to deliver marginal return, in both cost and performance, over current capabilities. While NASA has historically shared an interest in acquiring affordable access to space to support its programs in space exploration, permanent human presence in earth orbit, and continuous earth observation, NASA has differed from the Air Force on the need for a manned system. NASA's requirement in this area is especially time-sensitive since the Shuttle system will soon be 20 years old, and nearing the end of its 30-year design life (in 2010).

Most government and private sector studies have concluded that even by applying advanced technology, the cost of spacelift using expendable chemical propulsion rocket systems cannot be reduced by more than 50% over current costs. These same launch studies have concluded that only reusable launch systems offer the potential for truly revolutionary reductions in the cost of access to space. However, reusable launch systems also have significant challenges:

- There is widespread skepticism over the technology risk associated with producing a fully reusable single-stage-to-orbit (SSTO) launch system with adequate payload lift capacity. (The risk is not as pronounced with two-stage to orbit systems, although these systems have other disadvantages.)
- Development costs for reusable launch vehicles (RLVs) are relatively high, and the cost risk is assessed to be very high.
- Small shortfalls in the dry weight goals for an RLV system or the specific impulse (I_{sp}) of its engines result in little or no useable payload to orbit.

As a result, both Congress and government agencies have been reluctant to pursue the development of a fully reusable launch system, and have instead focused on programs to better understand cost, risk, and performance factors before committing to a full scale development program. These so-called "X" programs are an essential step enroute to an operational RLV and will be reviewed later in this chapter.

2.2 Background

The Air Force has expended a considerable effort in planning the modernization of its space launch capability. In the past decade, space launch has been one of the most thoroughly studied technology areas within the DoD.

2.2.1 Previous Launch Studies

The years 1992, 1993 and 1994 were marked by several studies on the issue of space launch, with affordability being the prime focus. Most recently, Congress (in the FY 94 Defense Authorization Act) directed DoD to accomplish yet another space launch study. This study, known as the *Moorman Study,* was able to achieve consensus among NASA, the DoD, the intelligence community, and the commercial sector on the preferred direction for space launch. The Moorman Study was the basis for President Clinton's August 1994 Space Transportation Policy, which gives NASA overall responsibility for reusable launch vehicles and the Air Force the lead for expendable launch vehicles. Importantly, on the topic of spacelift technology funding, the Moorman Study found that the current DoD enabling core technology program for spacelift is "significantly underfunded and lacks long term commitment and stability." The study recommended that the spacelift core technology program within DoD be increased from its current level (approximately $45M per year) to $120M per year by FY 96. A summary of the core technologies with the associated funding profile is presented in Figure 2-1. Note that the figure shows significant unfunded requirements in the outyears.

	Propulsion	Vehicle	Operations
Expendable Unique	Low Cost Engine Storable Propellants Storable Propellants Clean Solid Propellants Hybrid Propulsion	Low Cost Booster	
Common	Upper Stage- Propulsion Russian Engine Test Simple Pumps Chamber/Injectors Test Beds High Energy Fuels	Adaptive GN&C AI/LI Structures Composites Low Cost Mfg Man Tech	Automated Processes Heath management Non Destructive Inspection Leek Free Joints Fault isolation
Reusable Unique	Linear Aerospike Advanced Propulsion Preburner Turbopumps Tripropellants	Primary Structure Insulation Reliable Sensors CryoTanks Aerothermo	Recovery/Refurbishment

Total FYDP Unfunded Core Technology Investment $384M (CY94$)

94	95	96	97	98	99
$0M	**$45M**	**$89M**	**$86M**	**$83M**	**$81M**

Figure 2-1. Air Force funding for core spacelift technologies

2.2.2 Requirements and Air Force Planning

In 1992, the Air Force implemented a 25-year modernization planning process known as Mission Area Planning (MAP) to help guide planning, technology, and associated investment decisions. Air Force Space Command developed the following five top-level tasks for its Space Launch MAP:

- *Launch satellites in accordance with the national mission model*
- Operate the launch and range facilities
- *Perform transpace operations*
- *Recover space assets*
- Identify the launch requirements of the other sectors (commercial, civil, intelligence)

The highlighted tasks have significant technology implications. The results of the Mission Needs Analysis for these spacelift tasks identified deficiencies in the following areas:

- Affordability (the most pervasive deficiency)
- Schedule dependability (i.e., responsiveness, supportablity, and maintainablity)
- Launch rate and reliability
- Object recovery and return

2.2.3 Current Investment in Spacelift Technology

The current and planned US technology funding for spacelift consists of the following:

- Approximately $100M in FY 95, including $65M of Congressionally added funds not requested by the Administration
- Annual programmed funding of approximately $40-45M per year for FY 96-01
- NASA spacelift technology investment of approximately $70M per year 96-01
- NASA X-33 and X-34 program funding of approximately $800-900M for FY 97-00

A major portion of the Air Force effort falls under the Evolved Expendable Launch Vehicle (EELV) program. The EELV program will acquire a single family of expendable vehicles to launch the national mission model in the medium launch vehicle (MLV) and heavy launch vehicle (HLV) classes, which are currently serviced by Titan II, Delta, Atlas, and Titan IV. The commercial sector is likely to take the lead in small (less than 4500 lbs to LEO) launch vehicles in the near future. The Air Force can adapt the technologies that are developed commercially in this area and concentrate its technology investments in developing heavier-lift vehicles. EELV's objective is to reduce costs, maintain mission assurance, and improve reliability and operability within program cost constraints. First launch of the MLV class of EELV is set for 2001, with first launch of the HLV version planned for 2005. EELV is aimed at a 20-50% reduction in spacelift costs, with smaller improvements in responsiveness and reliability.

The major US RLV projects at this time are NASA's X-33 and X-34 programs. The X-33 is a sub-scale advanced technology demonstrator designed to support commercial and government decisions in 1996 and later regarding reusable launch vehicles, with the objective of leapfrogging future competition for space launch. The X-33 technologies are currently under development by Lockheed Martin, McDonnell Douglas Aerospace, and Rockwell International Corporation. The X-34, which is planned to fly in 1998, is a cooperative effort between NASA and Orbital Sciences Corporation for a smaller advanced launcher. The X-34 is intended to demonstrate technologies applicable to future reusable launch systems and to stimulate industry/government funded development of a reusable small launch vehicle with commercial applications.

2.3 Air Force Requirements for Launch Vehicles

Although expendable launch vehicles do not harbor the possibility of revolutionary (order-of-magnitude) reduction in the cost of access to space, they will be the likely mode for Air Force spacelift in the near term. A revolutionary reduction in launch costs (required to enable advanced missions) will, however, require investment in reusable launch vehicle technologies. The current work in progress at the component and system levels in both the EELV and NASA X-33 and X-34 programs will figure prominently in the development of new advanced launch concepts using chemical propulsion systems. However, it is unlikely that Air Force and NASA objectives for RLVs will be completely congruent. In particular, the Air Force has needs for rapid reaction and rapid turnaround (akin to aircraft operations) that will have no NASA counterpart in the foreseeable future.

The Air Force has also been interested in so-called transatmospheric vehicles (TAVs) that could augment generic RLVs. Military RLVs and TAVs are intended to be *operated and maintained like Air Combat Command aircraft*. The military needs a rapid-reaction (launch within a few hours of a decision), quick-turnaround (sortie-like operations), low-cost vehicle with minimal requirements for unique space launch ground infrastructure. It should be a space vehicle with operations costs and operability characteristics more akin to aircraft than today's spacelift systems. In most concepts, it has relatively small payload to orbit; it derives its utility not from simply space transportation, but, particularly for TAVs, as a multi-mission platform for such applications as quick-reaction reconnaissance, on-orbit inspection of friendly and potentially hostile satellites, and perhaps weapons delivery.

While existing national policy gives NASA the lead in developing RLV concepts and technology, it also provides for continued Air Force/NASA cooperation and collaboration. When applied to technology development, this division of responsibility is somewhat blurry because many of the reusable and expendable launch vehicle goals are similar (e.g., lower cost, simpler operations, high reliability). In particular, the USAF brings core competencies in operations, testing, and support activities from its aircraft operations legacy that are directly applicable to RLVs. A number of Air Force-led technology programs aimed at expendable launch vehicles directly support NASA's reusable launch vehicle program as well. The Air Force should participate in the X-33 program to provide technical support and to provide input for future vehicle development decisions. A sustained launch technology program will be necessary to make RLV/TAV systems a reality. The Air Force should continue developing and demonstrating technologies that fall into the following areas:

- Rocket propulsion

- Vehicle structures
- Launch processing and operations

2.4 Rocket Propulsion

Rocket propulsion capability is the most important technology necessary to enable many of the RLV applications envisioned for the future. Small increases in rocket engine specific impulse (I_{sp}), for example, translate into much more capable launch systems. Advanced lightweight, high-thrust-to-weight propulsion will only be achieved, however, through a combination of technology initiatives.

2.4.1 The State of the Art in Rocket Propulsion

Russian rocket engines represent the current state of the art in rocket propulsion. Russian rocket propulsion technology is advanced compared to US systems, particularly with respect to liquid oxygen/hydrocarbon engine development, tri-propellant engines, and operations. In particular, Russian engines are very robust, routinely use staged combustion cycles, and operate at higher chamber pressure than their US counterparts. Russian engines are being considered for use in several of the competing designs for EELV. The Space Shuttle Main Engine (which was the last large rocket engine developed in the US) is the only US staged-combustion-cycle engine, and it suffers from high manufacturing cost, lower than desired thrust-to-weight, and a lack of necessary robustness for RLV applications.

2.4.2 Technologies for Evolutionary Change in Rocket Propulsion

The Integrated High-Payoff Rocket Propulsion Technology (IHPRPT) effort is a national (government/industry) strategic planning process (patterned after a similar long-standing aircraft propulsion program) with the goal of improving rocket engine against several specific metrics. IHPRPT will be performed in three phases with specific goals for each phase, as shown in Table 2-1. These goals were chosen to be challenging but achievable to encourage the development of new technology. The goals will be demonstrated to full scale in integrated demonstrators at the end of each phase. For an example, the Integrated Power Demonstrator will demonstrate simplified, high reliability low-cost turbomachinery and thrust chamber component technology in an integrated engine demonstration at the 250,000 lb thrust level. The Upperstage Engine Demonstrator program will demonstrate a 50,000 lb thrust liquid oxygen/liquid hydrogen (LOX/LH_2) upperstage engine technology for use on the upgrades of the EELV and the next generation launch vehicles. Industry will thus be able to insert the technologies promptly and realize a return on investments before the end of the 15 year program.

Although the cost goals show a reduction in hardware and support costs of only 35% by 2010, the impact of achieving all of the goals simultaneously will provide the technology to reduce the cost to orbit by 80% of what today's technology can provide. The additional cost benefits are obtained from substantial payload increases (gained from I_{sp} and engine thrust-to-weight improvements) and reduced costs of failure.

The IHPRPT program is jointly run by both the government (DoD and NASA) and industry (both liquid and solid propulsion houses) with all participants fully endorsing the program goals. Government-sponsored and industry-IR&D-funded efforts are fully coordinated in the area of

rocket propulsion. With coordination from all groups, the IHPRPT process will naturally eliminate duplication of effort and insure the maximum return on investment of research and development funding. The program goals in rocket propulsion are technically feasible but are constrained by funding, which is currently a very limited. Increased, sustained funding will be needed to achieve these goals.

Table 2-1 Goals of the IHPRPT program

BOOST & ORBIT TRANSFER	**2000**	**2005**	**2010**
Reduce Stage Failure Rate	25%	50%	76%
Improve I_{sp} (sec)	14	21	26
Reduce Hardware and Support Costs	15%	25%	35%
Improve Thrust to Weight	30%	60%	100%
SPACECRAFT	**2000**	**2005**	**2010**
Improve Mass Fraction	15%	25%	35%
Improve I_{sp} (sec)	10%	15%	20%

Upper stage engines, used for transfers from LEO to higher orbits, benefit from many of the same technological advancements as booster engines. For upper stage applications, however, additional technologies are feasible. The Air Force is currently funding research in solar-thermal propulsion. The I_{sp} range for this type of engine is between 800 and 1200 seconds depending on the parameters of the particular design. Thrust is approximately 9 Newtons. Concentrated (10,000 suns equivalent) solar energy comes from two 7 meter x 9 meter off-axis paraboloidal thin film concentrators. Trip time from LEO to GEO ranges from 10 to 60 days depending on the thrust, payload, thruster type, and concentrator.

2.4.3 Technologies for Revolutionary Change in Rocket Propulsion

The highest-leverage technology area impacting launch vehicles is the development of high-energy-density materials (HEDM) for use as propellants, which offer the promise of significantly reducing both booster and upper stage weight and hence lowering launch costs per pound of payload delivered. While the existing USAF program of this name is oriented primarily towards rather modest near term improvements in I_{sp}, (in the range of 7-20 seconds), much more effort should be devoted to revolutionary advances in this field. If I_{sp} could be increased from today's limit of about 450 seconds to nearer the theoretical limit of 1500 seconds, payload mass fractions would increase (all other things being equal) by a factor of approximately four to six. While it is still not clear how this might be done with propellants capable of being contained in a reasonable structure, such an achievement would fundamentally change the nature of spacelift.

HEDM is already examining one advanced concept to use metals as fuel additives. Metal atoms or small molecules stored in liquid hydrogen, for example, could yield I_{sp} gains of 50 or 100 seconds, resulting in a 25% increase in performance in a system such as the STS. The long-term goal for energetic propellants should be an I_{sp} increase of much greater than 100 seconds. Material systems such as metallic hydrogen would produce such increases in I_{sp}. The use of computational chemistry techniques to enable the design of even more energetic propellants needs to receive increased emphasis, because such technologies could enable missions thought to be impossible by today's standards. The potential benefit of HEDM technology justifies a significant investment by the Air Force.

Another high leverage technology area within launch concerns materials that could withstand extremely high heat loadings (such as those generated in rocket engines) without failing. Engine specific impulse (which scales as the square root of the maximum temperature allowed in the combustion chamber) and thus engine thrust-to-weight ratios could dramatically increase if materials that could withstand extremely high heat loadings were available. Besides increasing maximum specific impulse, these materials would enable critical portions of the engine to be operated without the added complexity and mass of an active cooling system. Such dramatic improvements may enable such revolutionary concepts as the scramjet engine to become a reality; a scramjet would have the distinct advantage of taking its oxidizer from the atmosphere rather than carrying it along and hence could allow more of the vehicle mass to be devoted to payload. The potential benefits of the development of such materials justify substantial sustained development.

2.5 Vehicle Structures

Dry structural weight of an RLV comprises a significant portion of the vehicle mass fraction (propellant mass divided by total vehicle mass) and must be minimized if RLVs are to become a reality.

2.5.1 The State of the Art in Vehicle Structures

Today's vehicle structures are primarily aluminum, with some use of composites. All current vehicles capable of placing a payload in orbit consist of multiple stages. Based on the current level of technology, with the specific impulses available in today's engines, a single-stage-to-orbit vehicle is not capable of achieving positive payload to LEO. Advanced compounds like aluminum-lithium (Al/Li) would offer substantial weight savings, but are not yet widely available.

2.5.2 Technologies for Evolutionary Change in Vehicle Structures

The NASA report on the Access to Space study concluded that advances in technology areas such as composite cryogenic tanks and thermal protection systems are critical to making a fully reusable launch vehicle feasible. Ongoing cryogenic tank efforts address metal-lined tanks (relying on the liner to contain the propellant) because, to date, all unlined tanks have leaked at the penetrations and at the composite laminates. A new program, looking at unlined tanks, is planned to begin in FY 95, with the goal of decreasing tank cost and weight. Research is being done to find new composite structural materials that are impact-resistant and resist cracks and delaminations when exposed to extreme and cyclic conditions. Payoffs to the Air Force include reduced cost of manufacturing fuel tanks that are light and reliable while increasing the load

carrying capabilities and reducing life cycle costs. Composite structures and tankage offer a potential of replacing traditional metallic launch vehicle structures due to their high strength-to weight ratio, flexibility in design, custom tailoring of desired properties, and the ability to exist in different environments. According to one study, the use of composite materials could reduce tooling, part count, manufacturing lead time, cost, and structural weight by as much as 40%. The Air Force should continue to invest in concepts to reduce vehicle dry mass while maintaining the required structural stiffness, integrity, and robustness to enable low life cycle cost.

Similarly, considerable effort is being focused in the area of thermal protection systems. The rigid tiles currently used on the Shuttle require extensive, expensive, manual inspection and maintenance after each flight. Current programs are pursuing more damage-resistant, less brittle, lighter-weight tile concepts. Further efforts are planned to look at better approaches for attaching thermal protection systems to the vehicle structure, or even to the propellant tanks themselves, to further reduce weight, reduce cost and increase reliability.

2.5.3 Technologies for Revolutionary Change in Vehicle Structures

In addition to the need in rocket engines, high temperature materials that do not require active cooling are a vital area of technology investment for advanced thermal protection systems. Such materials will be essential for military TAV's and RLVs. Advanced thermal protection systems will become particularly important if air-breathing (e.g., Scramjet) propulsion concepts are used for a large portion of the TAV flight profile within the atmosphere. For advanced vehicle concepts, material systems capable of 4000K on one surface and cryogenic temperatures of 4K on the other side will be required for use in engines and structures.

Vehicles may be designed with the cryogenic tanks integrated for vehicle load structure, such as wing elements, while still requiring a thermal protection surface. For RLV's, the high temperature materials used for the thermal protection system will also have a requirement to be operable and more importantly, field-repairable. Integrated structures combining reusable cryogenic storage with a thermal protection system would reduce the overall dry weight of the vehicle. In addition, the integrated structure would include self-diagnosing sensors, enabling the vehicle to report on its condition, a critical capability if short turnaround time is to be achieved. Thus lightweight integrated structures combining reusable cryogenic storage, thermal protection, and self diagnostics to enable a *responsive* reusable launch capability are revolutionary technologies in which the Air Force must make a sustained investment.

2.6 Launch Vehicle Processing and Operations

Advances in launch vehicle operations are as critical as the design of the vehicle itself to ensuring the responsiveness necessary for Air Force spacelift in the 21st century.

2.6.1 The State of the Art in Launch Vehicle Processing and Operations

Today's US launch systems are widely criticized as being non-responsive in terms of the time it takes from a decision that a launch is needed to the actual launch. Many factors are responsible for the current situation, including management philosophies, but the response time for the current systems varies from approximately 30 days to more than 270 days. Today's process includes substantial amounts of on-pad integration, checkout, test, and verification that

is personnel-intensive and thus contributes to the high cost of launch. The US launch infrastructure, concentrated for the most part in its two coastal launch locations at Cape Canaveral AFS and Vandenberg AFB, is also not conducive to rapid pad turnaround and relaunch.

2.6.2 Technologies for Evolutionary Change in Launch Vehicle Processing and Operations

The EELV/RLV will incorporate improvements in launch processing and operations to reduce costs. The improvements will come from design changes and incorporation of technologies that have been under development, but have not yet been utilized in US launch vehicles. Design changes will allow more of the processing and checkout operations to be accomplished off-pad, resulting in more efficient utilization of the launch facility. Improvements in propellant handling and loading, as well as improvements in the availability and reliability of downrange systems for safety and tracking are currently being realized as systems are being automated and generally modernized. In addition, integrated health monitoring technologies will expedite the verification and checkout of the vehicle and pad systems. Some of these improvements may come from incorporation of Russian automated launch operations techniques. Finally, X-33 and X-34 demonstrations will serve as an "operations laboratory" that will allow the Air Force and NASA to learn how to operate rockets and space hardware with manpower, maintenance, and support characteristics akin to conventional aircraft. The Air Force should closely monitor improvements in launch vehicle operations that are driven by the commercial sector. A number of commercial interests are proposing constellations of many tens to hundreds of satellites for global communications systems. For these systems to be commercially viable, the cost of access to space must be reduced. The commercial sector has aggressively pursued efficiencies in operating satellites and is likely to do the same when launching them.

2.7 Recommendations for Investments in Launch Vehicle Technologies

The Air Force should follow a carefully targeted plan of investments in launch vehicle technologies, investing for both revolutionary and evolutionary improvements in launch vehicle systems.

2.7.1 Revolutionary Launch Vehicle Technologies in Which the Air Force Must Invest

Several key launch vehicle technologies offer the possibility of a substantial increase in the exploitation of space by the Air Force, the potential impact of which is so great that the Air Force must invest now. These technologies are:

- High energy density chemical propellants to enable spacelift with high payload mass fractions; specific impulses of 1000 seconds or greater (in high-thrust systems) should be the goal of this effort
- Lightweight integrated structures combining reusable cryogenic storage, thermal protection, and self diagnostics to enable a *responsive* reusable launch capability
- High temperature materials for engines and rugged thermal protection systems

2.7.2 Evolutionary Launch Vehicle Technologies in Which the Air Force Should Invest

The Air Force should invest for evolutionary improvements in performance or reduced life-cycle costs to its systems. The technologies that offer such benefits in the area of launch vehicles are:

- Engine technologies (e.g., turbomachinery)
- Upper stages (Alternate propulsion concepts will be addressed in the payloads chapter of this report.)
- Lightweight vehicle structures (e.g., aluminum-lithium (Al/Li) or advanced composite tankage)

2.7.3 Commercially Led Launch Vehicle Technologies

Another set of technologies that will allow for evolutionary change in launch vehicle technologies will be driven by the commercial sector. These technologies merit minimal investment by the Air Force, yet the Air Force should invest as necessary to adapt these technologies to its needs. These technologies are:

- Small launch vehicles (less than 4500 lbs to low earth orbit)
- Technologies for vehicle operations

Finally, the Air Force should reexamine the overall level of funding devoted to spacelift technology. While spacelift investment should be fully coordinated and integrated with the long term technology program within NASA and industry for the next generation RLV, it is important to realize that that some launch requirements are unique to the DoD. With the exception of the Space Shuttle work in the 1970s and the some SDIO technology spending in the late 1980s, launch vehicle technology funding (and associated laboratory manpower) within the Air Force has been on a relatively steady decline since the early 1960s. This trend must be reversed if the Air Force is serious about space control and exploitation as core missions. The current relative level of technology funding is inconsistent with Air Force aspirations to develop space as one of its core competencies.

3.0 Spacecraft Bus Technologies

3.1 Introduction

The continuing development of advanced spacecraft technology is essential in order to increase spacecraft capabilities and reduce costs while lowering weight and volume. Over the last few years, two basic philosophies have emerged. The first philosophy is to integrate many functions in the same spacecraft, thus producing fairly large spacecraft with many capabilities. These complex spacecraft use state-of-practice technologies, have a very small payload mass fraction, tend to be very expensive to develop, and have to be launched on large launch vehicles. The complexity of these multi-function systems is closely related to the number and type of bus technologies required to support the various payload subsystems. The second philosophy uses a different approach to building spacecraft, integrating very few payload instruments and using the most advanced lightweight technologies available (state-of-the-art). These types of spacecraft tend to be relatively small with a much larger payload mass fraction. While these smaller spacecraft have limited capabilities, they are much more affordable than the larger systems due to the basic lower cost of the spacecraft and the use of smaller, much less expensive launch vehicles. With the continuing development of spacecraft technologies, the capabilities of these smaller spacecraft can be enhanced considerably. In the near future, the second design philosophy can be applied to most operational systems.

Spacecraft bus technology in the US has been funded primarily by DoD, NASA, and the commercial sector. Within the DoD, the Air Force continues to be the major developer of satellite technologies. This leadership must continue not only in near term technology evolution, but also in the development of revolutionary technologies that can produce an order of magnitude improvement in capabilities at a reduced cost.

Although spacecraft perform a multitude of functions, every spacecraft, regardless of its function, contains support systems that perform essentially the same tasks. These systems can be divided into:

- Spacecraft structures
- Electrical power systems
- Attitude control systems
- Command and data handling systems
- Thermal control systems
- Propulsion systems

In addition, there is the consideration of the survivability of the spacecraft that determines some of its design. Each of these aspects of spacecraft design is ripe for a significant evolution in the near future.

3.2 Spacecraft Structures

Reducing weight in spacecraft structures has, to date, been a matter of building the structures out of lighter materials while still maintaining the strength, stiffness, and other properties required

for the structure. Improvements in materials are likely to occur over the near term; a more radical approach is to integrate different functions of the spacecraft bus into the materials that form its structure.

3.2.1 The State of the Art in Spacecraft Structures

Over the last 25 years, the use of metal matrix, metal resin, and carbon-carbon composite materials as spacecraft materials and structures have reduced the spacecraft weight considerably. The structural weight of an aluminum spacecraft is about 23% of the total spacecraft weight. Composite materials were first introduced in the spacecraft in the mid 70s as secondary structures for reflectors and feed supports. Since then, the use of composites has propagated to the entire spacecraft, to the point that most spacecraft designed today use composites to decrease the structural mass fraction. Figure 3-1 shows that with the integration of composite primary structure and many composite secondary structures, structural weight is currently only about 7% of the total spacecraft weight.

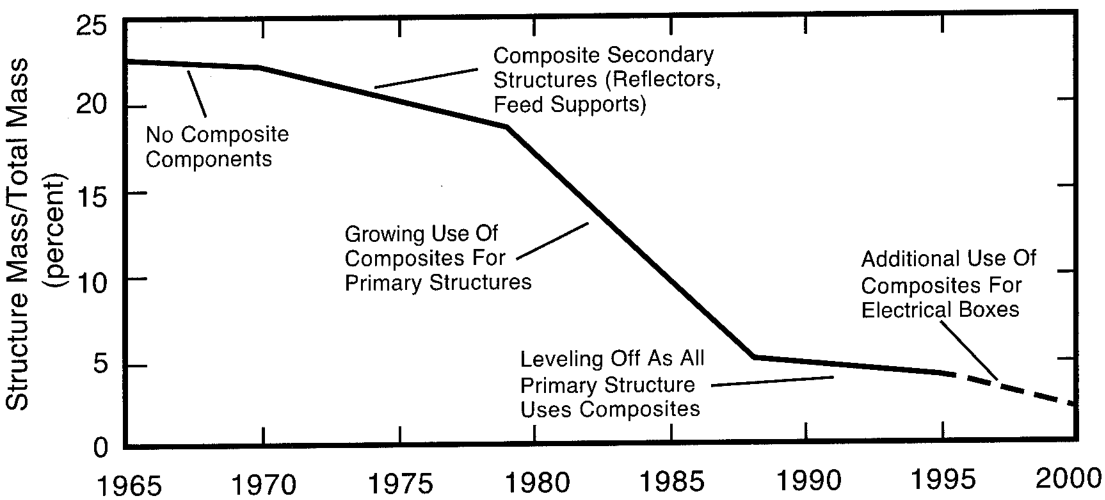

Figure 3-1. Evolution of spacecraft structure as a fraction of spacecraft mass

Spacecraft structures today are being designed predominantly with metal alloys such as 7075 aluminum, organic composites such as graphite lamina, or metallic composites such as silicon carbide on aluminum. Polycynate-ester resin systems (PERS) are now being tested for space applications. PERS have low outgassing and are non-hygroscopic, which prevents potential material condensation onto critical optics. Additionally, significant improvements have been made in the design and manufacturing of materials and structures. Instead of hand machines, workstation computer aided design and precise laser cutting (computer aided manufacturing) are being used almost exclusively today. Current spacecraft designs use structural elements on which electronics boxes and other elements are mounted. Cabling and waveguides are used to interconnect these subsystems.

3.2.2 Technologies for Evolutionary Change in Spacecraft Structures

The spacecraft designed in the early 1990s used trusses and bi-stem beams as deployable structures, with a large ratio of deployed volume to stowed volume. If the present level of funding continues in the development of structures, lightweighting will reduce mass by about 60% over the next ten years. However, the coupling between the displacements of deformable structures and the performance of control systems has led to the development of control/structure interactions. Smart structures using piezoelectric sensors and actuators can provide active damping and jitter suppression, meeting structural requirements such as stiffness and dimensional stability with greatly reduced mass. The Air Force should make the investment required to develop control-structure interactions with active control for vibration suppression.

Most spacecraft have a variety of requirements for electro mechanical devices for precision articulation, separation, appendage release, and so forth. Many of these devices have been pyrotechnically initiated. Innovations in mechanical devices and applications of shape memory and phase change materials are maturing that can not only reduce cost and weight of these devices, but are low-shock, low-vibration, and capable of being activated without use of pyrotechnics. Furthermore, the devices are resettable and completely testable prior to flight use. They are inherently more reliable because of the reduced number of parts. Significant indirect savings are possible by eliminating hazardous operation associated with pyrotechnics. Every effort should be made to avoid debris generation so as not to increase the orbital debris. The Air Force should make the investment necessary to bring this class of devices through qualification and into general use.

Cabling on a spacecraft bus is typically very heavy, and the touch labor in assembling and testing the cabling is significant. Spacecraft bus hardware could be integrated using advanced structures that meet the thermal, electrical, and structural functions. Designing of such multifunctional structure would be made possible by advances in lightweight material development, high density electronics packaging, and advanced computer-aided design tools. In this approach, cabling and interconnects would be replaced by a multilayer network deposited on the structural substrate. Each layer of the multilayer network would perform a specific electronic function: power, ground, control, data transmission, and so on. This innovative approach would also allow electronic subsystems to be mounted directly on the spacecraft structure without the use of enclosures, resulting in unparalleled weight savings. This technology could enable, with the use of standard interfaces, the incorporation of thermal control into the multifunctional structures, and the integration of a satellite subsystems on the structural elements. In addition, it is conceivable to control the multilayer networks on the structural members through software and rerouting algorithms that control the interconnection of various modular subsystems, antenna elements, and microelectromechanical-systems-based devices embedded in the structural elements. To bring this technology to fruition, the Air Force needs to invest in multifunctional structures, microelectromechanical systems (MEMS) technologies, and advanced electronics packaging technologies specifically directed toward space systems.

Another issue that will affect the design of future spacecraft structures is the requirement to reduce the vulnerability of space assets by making them hard to detect. Low-observable technologies are often considered to be materials issues, but reducing a spacecraft's

electromagnetic signature means much more than finding materials that are non-reflective, because each surface of a spacecraft has a function to perform, whether collecting solar energy, radiating thermal energy, collecting or broadcasting radio frequency (RF) energy, or sensing other portions of the electromagnetic spectrum. Systems-level design considerations (for example, placing radiator panels so that they face into space) and overall systems architectures (such as satellites that are passive until they need to perform their particular function) come strongly into play. It is necessary to consider carefully what portion of the spectrum an opponent will be searching (whether RF, visible, or infrared (IR)) to effectively hide a satellite. Technologies for spectrum-selective reflection and absorption is one area that the Air Force should pursue, along with materials that are both stealthy and structural.

3.3 Electrical Power Systems

Presently about 25% of the weight of a spacecraft is used to generate the electricity required to operate the various subsystems. There are three basic elements in the power systems being used by today's spacecraft:

- Energy conversion systems. Most satellites collect solar energy, which the satellite cannot use directly. This energy must be converted into electrical energy to be useful to the satellite.
- Energy storage systems. Solar energy is usually available for only a portion of a satellite's orbit. Therefore, in addition to converting solar energy to electrical energy, a satellite must store energy onboard (usually in a battery) to be used during eclipse times.
- Power conversion systems. Electrical energy taken from storage must be converted into a useful form as required by a satellite's subsystems.

Although a power system consisting of solar cells, batteries, and DC-DC converters is most typical on spacecraft, it is not the only way one can conceive of powering a spacecraft, and innovative technologies for each of these basic functions are possible.

3.3.1 The State of the Art in Electrical Power Systems

Photovoltaic solar cells are used by spacecraft to convert solar energy to electrical energy. Early cells were thick, discrete cells, made out of silicon and laid out on rigid panels. Thin discrete silicon cells were used throughout the 1980s; however, silicon cells have been limited to about 14% efficiency. In the early 1990s, smaller Gallium Arsenide (GaAs) cells were developed and integrated on flexible panels with a cell efficiency over 18%. Now, in 1995, dual junction Gallium Indium Phosphide/Gallium Arsenide ($GaInP_2/GaAs$) cells on a germanium substrate have shown 23% efficiency. With continuing funding, triple junction thin-film cells will be built and manufactured in the near future, obtaining roughly 30% efficiency.

Nickel hydrogen batteries have replaced nickel cadmium batteries in most of today's spacecraft. Recently, the nickel hydrogen common pressure vessel battery with a specific energy of 55 Watt-hours per kilogram (Wh/kg) has produced twice as much energy density than a design using individual pressure vessels. Additionally, nickel hydrogen batteries can tolerate a much larger depth of discharge than nickel cadmium batteries without degradation.

The energy stored in the battery has to be converted efficiently for use by the various spacecraft subsystems. Early spacecraft obtained about 50% power conversion efficiency using discrete components. The present state of practice uses linear integrated circuits with bipolar transistors to achieve about 65% efficiency. However, the present state of the art is to use hybrid application-specific integrated circuits based on metal oxide semiconductor (MOS) transistors to obtain about 80% efficiency.

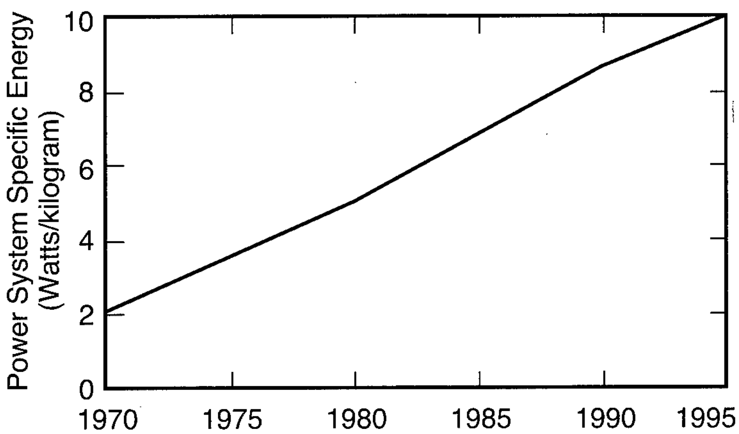

Figure 3-2. Evolution of power system specific energy

Overall, the efficiency of the entire electrical power system is measured by calculating the power system specific energy. The present state of the art is 10 Watts per kilogram (W/kg). Figure 3-2 shows the trend in the development of the electrical power system over the last 25 years. The results are very striking. For example, to produce 1 kiloWatt (kW) of power in 1970, about 460 kg was required. Now, in 1995, the same power can be provided with about 92 kg.

3.3.2 Technologies for Evolutionary Change in Electrical Power Systems

Over the last ten years, most spacecraft have moved to the 18% efficiency GaAs cells. GaAs cells are more radiation-tolerant and have lower loss of power with temperature than silicon cells. However, silicon panels continue to be at least 20% cheaper than GaAs panels. Instead of debating the advantages of today's cells, it would be better to leave both of these technologies behind and to begin to fund the development of wideband cells with expected efficiencies between 21-30%. The Air Force should assist the commercial sector to develop dual junction $GaInP_2$/GaAs cell manufacturing technologies, to build large-area arrays, and to increase the yields to levels comparable to GaAs cells. At the same time, the Air Force should proceed to fund the development of triple junction cells and quadruple junction cells to continue to optimize the yield from the sun. With a well-managed effort and increased funding, 30%-efficient triple junction cells should be able to be manufactured in large scale at the beginning of the 21st century. Other energy conversion alternatives should also be funded. The Air Force should fund the development of Fresnel concentrator arrays as the main source of spacecraft energy conversion. Preliminary tests (in sample sizes) of GaAs/GaSb concentrator arrays have already yielded 30% efficiency with optimum solar pointing. These high-efficiency solar arrays would have a major impact on the design of spacecraft. This work should continue, not only to push the theoretical limits of these concentrator arrays, but also to examine manufacturing techniques and the impact on spacecraft operations of using such cells.

An alternative technology to high efficiency cells is in thin film photovoltaic materials such as Copper Indium Diselenide (CIS) or Cadmium Telluride (CdTe). Cells could be monolithically

integrated by scribing the circuits directly on to the thin film, which could be produced in large area on flexible substrates to achieve an order of magnitude improvement in cost and weight metrics ($100/Watt, 300W/kg for arrays). Because efficiency is only predicted to be in the 10-15% range, relatively large surfaces would be required, but this is acceptable for many applications due to the small storage volume of the thin flexible material.

Even though the Nickel-Hydrogen (NiH_2) common pressure vessel batteries have shown energy density of about 60 Wh/kg, they appear to be reaching their theoretical limit. Lightweight lithium ion batteries are expected to increase energy densities to approximately 80 Wh/kg. However, there are currently severe limitations in the number of cycles that lithium ion batteries can withstand. These limitations have to be overcome to produce a reliable lightweight battery with an energy density of 110 Wh/kg or more. The coordinated Air Force and NASA programs to develop lithium batteries will be aided by commercial terrestrial development for computers, cellular telephones, and cameras; however, the funding to develop the large capacity cells required for spacecraft energy storage is not being planned. The Air Force has plans to build and flight test a sodium sulfur battery in the next few years, but a significant financial and managerial effort is required to take advantage of the potential benefits expected from sodium sulfur batteries.

Another energy storage device that appears to have a tremendous potential is the electro-mechanical flywheel battery (EMFB). Recently developed EMFBs have shown over 60 Whr/kg, 90% depth of discharge, and long life (on the order 15 years). EMFBs can also be used as energy momentum wheels, providing both the energy storage capability and the capability to perform small spacecraft movements. For efficient flywheel energy storage and conversion, the bearing must be extremely low friction. A hybrid superconducting magnetic bearing has recently been designed and tested. A flywheel energy storage prototype has been constructed for testing bearing friction loss and characterizing the dynamics of the rotor. The hybrid bearing design uses magnetic forces from permanent magnets for levitation (for ground-based application) and high temperature superconductor YBCO in between the magnets for stabilization. A 42 lb flywheel currently can rotate up to 6000 RPM with stored kinetic energy of 8 Watt-hours (Whr). The result from the recent rotor spin-down experiment indicates an average frictional energy loss of less than 2% per hour in a vacuum of 10^{-5} Torr, with imperfect system alignment and rotor balance. System dynamics studies have been conducted to improve upon the energy loss and rotor-bearing modeling. Projections are for the next generation flywheel to have losses less than 0.1% per hour. The energy storage for such devices should scale as the square of mass. The Air Force should invest in the development of this promising EMFB technology to be used not only for energy storage but also as momentum wheels.

Evolutionary improvements in power conversion should continue from the present state of the art of 80% conversion to over 90% in the next ten years without any increase in the funding of this technology. Power conversion today is being accomplished by applying high frequency conversion using metal oxide semiconductors field effect transistors (MOSFETs) and high-frequency, high-voltage Schottky diodes. The commercial sector will continue to integrate the latest electrical devices.

Solar thermal-to-electric power conversion began in the 1950s with the introduction of the solar cell. In the 1980's, solar thermal propulsion combined forces with electric power conversion, becoming known as solar bi-modal power and propulsion. Solar bi-modal power and propulsion

systems are similar to solar thermal propulsion systems in that they use the same concentrators and have a heat exchange medium as an absorber. There is one major difference: solar thermal propulsion systems have a separate, conventional electrical power conversion system while solar bi-modal schemes include the electric conversion system as part of the propulsion system, using the enormous amount of thermal energy available from the heat absorber to supply heat for thermionic diodes or thermoelectrics.

3.3.3 Technologies for Revolutionary Change in Electrical Power Systems

All current spacecraft are either power limited or restricted in some measure by inadequate electrical power. Power limitations impose restrictions on the communications and propulsion subsystems and currently make large space-based radars and space-based weapons relatively unfeasible. A revolutionary change in capabilities will result from power technologies capable of providing large amounts of power onboard satellites. Large amounts of power will be enabling on spacecraft in the same sense that large amounts of random access memory have been enabling in personal computers. If power is not an issue, then previously hard applications become easy and new applications become possible. Evolutionary development of solar-array-based power technologies will see improvements to tens of kilowatts on satellites over the next decades. However, all solar collection systems in Earth orbit are limited by the solar constant of 1.4 kiloWatts per square meter. Large powers from solar collectors require large collection areas. For substantially larger powers (> 100 kW), several different types of technologies will have to be explored. Powers of this level will make large space-based radars, space-based directed energy weapons, and the use of high-performance electrically driven maneuvering technologies possible. A natural technology to enable high power is nuclear power in space; however, this technology has to date been considered unacceptable due to political and environmental limitations. Thus it is desirable to develop other technologies that may provide large power levels in space. In addition to continued development of safe nuclear systems, two other sources of continuous power in space that should be explored are the concepts of electrodynamic power-generating tethers and power beaming from one location to another (e.g., from space to space). The development of these and other technologies for high continuous power will have a revolutionary effect and the Air Force should invest in these areas as well as continuing to invest in solar collection technologies.

Over the years, there have been several programs in nuclear powered spacecraft. NASA has been using Radioisotope Thermoelectric Generators (RTGs) for the interplanetary missions that generate a few tens of watts of power. Russia has flown nuclear reactors in space and BMDO has a joint program with the Russians (TOPAZ), under which the Defense department bought three of the reactors to do laboratory experiments. DoE had a program (SP 100) to use nuclear power in space and the Air Force had a nuclear propulsion program; these programs have been canceled. Nuclear power, however, remains one of the attractive alternatives in generating large amounts of power in space. To build a reactor for space applications has many challenging technical aspects including development of high-temperature lightweight materials, active cooling technologies, extremely radiation-hard and high-temperature electronics, and fail-safe system architectures. Setting the emotional issues of nuclear power aside, this technology offers a viable alternative for large amount of power in space. The Air Force should continue

efforts towards making a safe nuclear reactor in space a viable option. Existing joint programs with Russia offer a low cost alternative and should be pursued.

Electrodynamic tethers are essentially long wires that are drawn across the Earth's magnetic field. Just as in an electrical generator, the motion of a conductor across a magnetic field causes a voltage to be generated. If a current can be made to flow from the ionosphere through the tether and close back in the ionosphere, power can be generated. This power comes at the expense of orbital energy since the tether feels a drag force. Thus the tether effectively changes orbital kinetic energy to electrical energy and thus a continuous power system would be composed of a tether and a thruster to reboost the orbit. Alternatively, a system can be designed that uses a tether to extract energy during part of an orbit and then reboosts during another part of the orbit. Electrodynamic tethers can also be used as thrusters by reversing the current flow through the tether with an onboard power supply. In addition, electrodynamic tethers can also be used for momentum exchange between two tethered spacecraft. Since electrodynamic tethers work by using the voltage drop that comes from moving across the Earth's magnetic field, they are limited for effective use to orbits where the field is strong enough to give reasonable voltage drops. This limits tethers to orbits below a thousand kilometers from the Earth's surface. There are many technical issues to be resolved with high power electrodynamic tethers. These include the extraction of large currents from the ionosphere (tens of amperes), the emission of such large currents back into the ionosphere, and the dynamic stability of such large unidimensional conductors in orbit. This technology offers one high-risk, high-payoff way to achieve high powers in space and should be pursued.

Power beaming to a spacecraft using high power lasers offers another option for obtaining large quantities of power in space. In one concept, a high-power ground-based laser would be used to form a collimated beam onto the spacecraft. Solar arrays on the spacecraft would convert the laser power into onboard electricity for the spacecraft. In another concept, a space-based laser driven by a large solar array or a nuclear reactor could be used to beam power to another spacecraft. The Directed Energy Panel has identified many of the technologies that are needed for these concepts. In order for the receiving spacecraft to have small arrays, the arrays much be capable of processing equivalent power densities greater than 100 suns (140 kW per square meter). This would enable hundreds of kilowatts to be received by an array on the order of a few square meters in size. The limitation on such arrays is the availability of semiconductor materials that can convert such large power densities to electricity without large heat losses or without suffering permanent damage. The Air Force should invest in the basic research necessary to develop such materials as well as in pointing, tracking, and continuous high power generation in a laser device. As these technologies mature, the power beaming concept may become feasible for transmitting high powers to spacecraft; research will reveal where the limitations to this concept lie.

3.4 Attitude Control System (ACS)

A significant portion of the weight and volume of most spacecraft today is required to point the spacecraft. Precise pointing is required to execute controlled maneuvers, fulfill mission requirements (e.g., imaging specific areas of the Earth), and to maintain communications. Even though there have been significant advances in the development of this technology over the last

few years, continued funding and a well-planned management strategy will be required to make additional progress. The ACS is divided into three categories:

- Sensors used to compute position, velocity, attitude, and attitude rate
- Algorithms (usually implemented in software) to perform guidance, attitude determination, pointing control, momentum management, and associated functions
- Control actuators to maintain the orbit, attitude, and appendage/payload pointing

3.4.1 The State of the Art in Attitude Control Systems

To control the attitude of a spacecraft, it is necessary to establish a frame of reference. A stellar reference system is usually required to obtain an absolute attitude reference. Star sensors, sun sensors, magnetometers, horizontal scanners, and wide-field-of-view star cameras have been used for attitude determination. In the 1970s, the single star tracker was used with photomultipliers; by the 1980s intensified image tubes were built to produce slit scanners on narrow-field-of-view cameras. In the 1990s, wide-field-of-view star cameras using charged coupled device have produced a high precision stellar reference.

Gyroscopes are required to provide an inertial reference by measuring pitch, roll, and yaw attitude changes. The size of the gyro is closely related to its accuracy, which is normally determined by the drift rate. Over the last two decades, between a one- to two-order-of-magnitude reduction in weight and power has been obtained by switching from discrete electronics to ring laser gyros and interferometric fiber optic gyros. Figure 3-3 shows the overall trend in gyroscope development by the key industry partners.

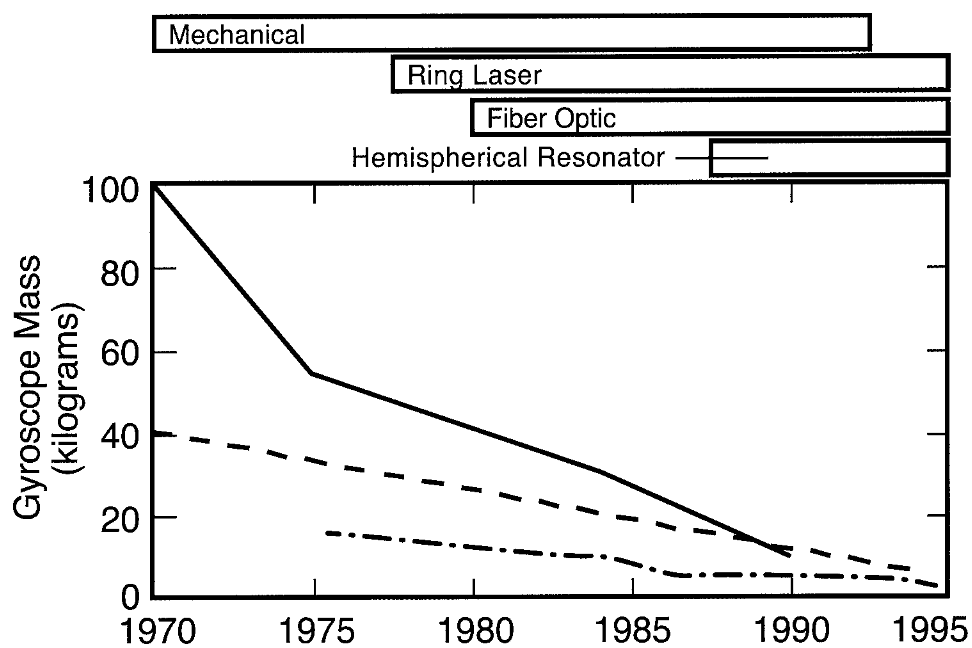

Figure 3-3. Evolution of gyroscope mass from three manufacturers

Once a satellite's attitude has been determined, and the desired corrections to this attitude have been calculated by onboard processors, it is necessary to change the orientation of the satellite in space by using some type of actuator. Reaction wheels, control moment gyros, momentum wheels, torque rods, and jets are normally used for such a purpose. Most spacecraft use one or more of these devices to control spacecraft motion.

3.4.2 Technologies for Evolutionary Change in Attitude Control Systems

The Air Force should fund promising developments in several aspects of ACS systems. The weight and power of stellar reference systems can be reduced further over the next ten years by using a wide-field-of-view stellar compass with charged coupled devices and an integrated computer system with a large star catalog. Similarly, the weight and power of inertial reference systems (gyroscopes) can be reduced; the most recent gyros use application-specific integrated circuits. Another factor-of-ten reduction in weight and power can be expected over the next ten years by continued development of interferometric fiber optic gyro using integrated optoelectronics. MEMS-based gyros with a drift rate less than one degree per hour are now being developed. A parallel technology development is Global Positioning System (GPS) subsystems, now coming into use for on-board trajectory state determination. Using multiple antennas (interferometry), GPS can also be used for attitude determination. Technology development leading to autonomous state and attitude determination with potential elimination of star sensors, gyros, and ground tracking should continue.

On-board high-speed computation and massive data storage have enabled the use of more sophisticated algorithms to perform required mathematical computations and data manipulation for the ACS. Continued development and test of new algorithms will be required to reduce cost (reusable software) and implement modern algorithms (such as neural nets and fuzzy logic) for improved performance, increased autonomy, and fault detection and recovery. In some cases, computational power could replace sensors.

The control moment gyros are where the biggest improvement in ACS systems can be made over the next ten years, by developing control moment gyros on the order of a few pounds able to achieve a pointing accuracy on the order of a few arc seconds. Electric propulsion, a revolutionary technology that will be discussed later in this chapter, will introduce new requirements on ACS components.

3.5 Command and Data Handling Systems

Spacecraft command and data handling systems typically have three elements:

- Processing systems
- Data transfer systems
- Data storage systems

Although one could conceive of a satellite that does not store data (communications satellites essentially perform this function), most satellites have the capacity to store data onboard for transmission to the ground at a later time.

3.5.1 The State of the Art in Command and Data Handling Systems

During the 1980s, the first 8- and 16-bit microprocessors were used in the spacecraft industry with capabilities of several kilo instructions per second (KIPS). These early processors were fabricated using flat packs on multilayer boards with total of about 4 megabit (Mbit) memory. By early 1990s, more powerful 32-bit processors, built using surface mount techniques on flexible printed circuit boards, were operating at tens of millions of instructions per second (MIPS) with about 16 Mbit memory. One key metric to evaluate the performance of spacecraft processors is the number of MIPS per Watt. Figure 3-4 shows the trend in processor performance. Since the draw-down in the defense budget beginning in 1990, the spacecraft computer market has been increasingly driven by the commercial market. The spacecraft computer industry is very effective in its design choices, separating systems and processors into different levels based on mission criticality. Table 3-1 shows the guidelines being used by industry to select processors for space applications.

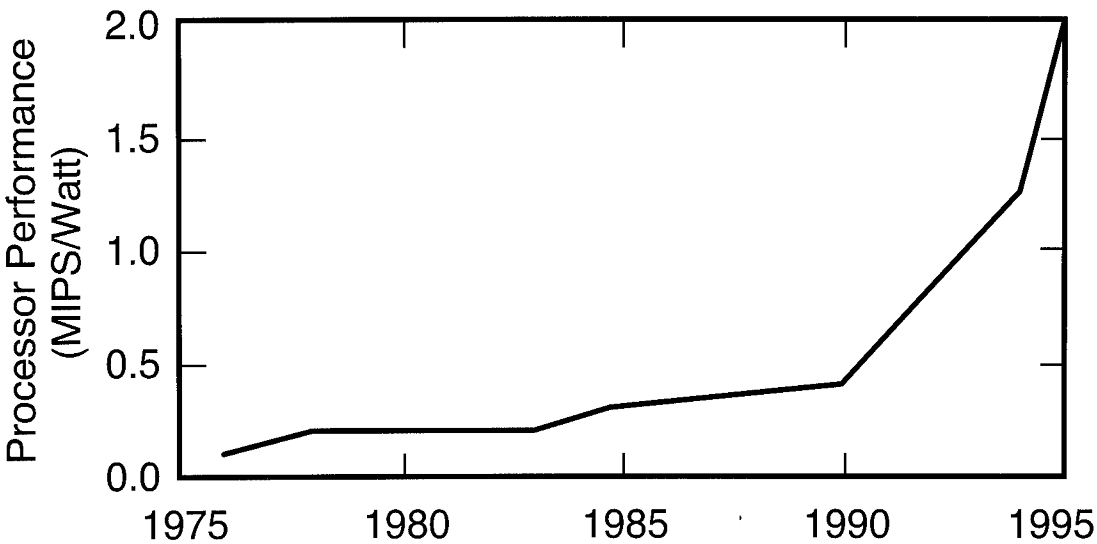

Figure 3-4. Evolution of processor performance

Most modern spacecraft data handling systems operating today use the MIL-STD-1553 interface at 1 megabit per second (Mbps). However, there are two basic limitations in the use of wiring cables for data transfer: weight and speed. Therefore during the last few years a new standard, MIL-STD-1773, has been developed, specifying the use of fiber optics for data transfer at 2 Mbps.

During the last ten years, there has been a tremendous growth in computer solid state memories. Presently, a ten-pound, 256-gigabit-per-second (Gbps), 4-gigaHertz (GHz), solid state memory can be built by using 16 Mbit dynamic random access memory (DRAM) elements. There are other types of memory that are essential for the successful operation of the space

systems. Because space systems have to operate in the hostile natural environment of space, static random access memories (SRAMs) are normally used in the processors along with non-volatile memory. In late 1980s 64 kilobit (kbit) radiation-hardened SRAMs became available. 256 kbit SRAMs appeared in the early 1990s, with 1 Mbit SRAMs on the horizon in 1996.

Table 3-1. Processor selection guidelines

Class	Error Tolerance	Function	Processors
Experiment	Loss of subsystems and daily upsets acceptable	Signal processing Data handling and formatting Onboard processing Data reduction	DSP Integer Floating point
Operational	Yearly upsets tolerable/level mitigation	Signal processing Data handling and formatting Data reduction	DSP Integer Floating Point Sequencer
Mission critical	Failure or upset could end mission	Attitude control Ordinance control Command and telemetry	Sequencer Integer

3.5.2 Technologies for Evolutionary Change in Command and Data Handling Systems

There are tremendous technological advantages and cost savings that can be achieved by harnessing the explosion of commercial electronics to the advantage of the space industry. Given the rapid advances of the commercial market, it is logical to expect spacecraft to have 64- or 128-bit processors operating at tens of MIPS per Watt in the next five years. These spacecraft processors will be able to perform 100 to 1000 MIPS with internal memory of 256 megabytes or higher. Although information processing technology is evolving rapidly in the commercial sector, the Air Force has unique needs that the commercial sector is unlikely to address. While the semiconductor industry has mapped out an aggressive plan to increase the performance of silicon integrated circuits, there is little commercial effort in radiation hardening of electronic devices

and the commercial sector is unlikely to address these specific needs. Air Force requirements in this area stem primarily from the perspective of spacecraft performance and survivability; the unique timeliness requirements of DoD will require more data processing tasks be performed onboard future spacecraft. The Air Force should invest in innovative techniques for radiation hardening of electronics and should ensure that radiation-hard manufacturing lines for high performance chips are maintained in the US. As commercial space develops, industry will be more likely to support a radiation-hard electronics industry, so investment today by the Air Force is likely to sustain a critical technology that will benefit both national and commercial interests in the next 30 years.

For data transfer applications, optical fibers are an attractive substitute for copper wires, because fibers would have a higher bandwidth and would weigh much less than cables. Entire spacecraft data buses operated exclusively with fiber optic cables should become operational during the next few years. The Air Force should invest to adapt commercial data bus standards to the space environment. Technology efforts should be directed towards developing and space qualifying commercial, non-proprietary standards to future space systems. The Air Force must take the lead in developing a framework for adapting commercial electrical interface standards at the subsystem and system level. Standard interfaces coupled with the adaptation of standard bus protocols of an open architecture will have a profound impact on the design, integration, and checkout of a space system, thereby reducing cost of ownership of the space system.

The basic memory element is likely to be 64 megabytes in 1996 and 1 gigabyte at the end of the century. This new technology development promises an enormous capability to store huge amounts of data in the spacecraft. The Air Force should not just depend on the commercial computer market to develop this technology and attempt to use it in the spacecraft. There are serious concerns about the radiation susceptibility of DRAM memory. As the memory elements become more compact, they are expected to be more radiation sensitive. Therefore, the Air Force should develop a careful program to continue to test the latest DRAM technology and invest in innovative radiation hardening technologies to ensure proper operation during future spacecraft operations.

Low-power, higher-density memories are essential to sustain the performance of future high performance processors. The Air Force should invest in technologies that will dramatically increase the memory densities for future space systems. Technologies such as fully depleted silicon on insulator (SOI) technologies offer the possibility of low power devices and the potential to adapt commercial capabilities to meet the unique Air Force requirements.

As the operation of space systems become more autonomous, non-volatile memory becomes more essential. Currently 64 kbit magneto-resistive RAMs (MRAMs) are becoming available with 1 Mbit MRAMs in the near future. The Air Force should invest in the development of higher-density non-volatile memories. Dramatic advances in higher density memories are essential and some of the technologies that offer great promise are ferroelectric RAMs, vertical Bloch memories, and memories based on calcoginates.

3.6 Thermal Control

Thermal control is critical to the survival of a spacecraft. A spacecraft is subject to thermal loading from solar radiation and from waste heat production by its onboard systems.

3.6.1 The State of the Art in Thermal Control

The combined evolution of high power payloads and light weight structures has made spacecraft thermal control an increasingly difficult problem. The state of the practice is to use a conductive metallic structure to act as a thermal capacitor and then to dissipate heat through radiators. More recently, heat pipes (both fixed and variable conductance) have come into common use to conduct the heat to the appropriate radiators. Carbon-carbon structures are in development to serve as structural elements and take advantage of the high conductivity of carbon fibers, however, the limits of passive thermal control are rapidly being reached. Current technology in passive heat dissipation is 50 Watts per square centimeter; active heat removal can achieve an order of magnitude higher heat flux. Currently there is no ability to interface directly with the multi-chip module (MCM) technology being used for high density electronics packaging.

3.6.2 Technologies for Evolutionary Change in Thermal Control

The Air Force needs to continue investments to develop active thermal control systems for high specific power applications. One major technical challenge is to achieve heat exchanger efficiency within a very small structure and to achieve high conductivity between this structure and an integrated electronics package. With the increased density of electronics components and the possibility of integrating the communications systems along with the RF communications systems in the MCM technologies, it is necessary to invest in innovative active and passive thermal control system. The Air Force should invest in MEMS-based coolers for high power chips, modules, and electronics packages. The Air Force should also invest in highly reliable no-moving-parts coolers and vibration suppression systems.

3.7 Propulsion

The most dramatic possibility for revolutionary change in spacecraft bus technology would be an improvement in the ability of a satellite to maneuver. This will be enabled by a move from chemical thrusters to electric propulsion for spacecraft maneuvering.

3.7.1 The State of the Art in Propulsion

No significant advances have occurred in the development of chemical spacecraft propulsion during the last 20 years. Most spacecraft continued to use hydrazine as a monopropellant and mono-methyl-hydrazine (MMH) and nitrogen tetraoxide (N_2O_4) for bipropellant systems. During this timeframe, small improvements have been obtained in specific impulse in the monopropulsion system by changing the pressure-fed titanium tank with neodymium nozzle to a piston-pumped system. However, over the last twenty years, the specific impulse of propulsion systems have remained between 200-225 seconds for monopropellant and between 300-315 seconds for bipropellant. Since the propulsion system constitutes approximately 35% of the wet weight in today's spacecraft, it is necessary to look beyond chemical propulsion to electric propulsion to find breakthroughs in propulsion systems.

3.7.2 Technologies for Revolutionary Change in Propulsion

Electric propulsion is a revolutionary technology that can enable moving spacecraft to different orbits, executing orbital plane changes, and performing routine spacecraft attitude changes. Electric propulsion has a tremendous potential for reducing spacecraft weight, and

that would allow the use of smaller launch vehicles with dramatic cost savings. There are three types of electric propulsion: electrothermal (e.g., arcjets), electromagnetic (e.g., plasma engines), and electrostatic (e.g., ion engines). A typical specific impulse is 450-1000 seconds for arcjets, 1500-2500 seconds for plasma engines, and 2000-3500 seconds for ion engines. The three categories of thruster technologies are shown in Table 3-2. Thrust levels are currently very low (fractions of a Newton) and need to be improved for many applications. The power required for an electric propulsion system is proportional to the specific impulse and could require tens of kilowatts of power.

Table 3-2. Classes of Electric Propulsion Systems

Thruster	Specific Impulse (seconds)	Thrust (Newtons)	Propellant
Electrothermal			
Resistojet	300-850	0.125-0.5	N_2H_4, H_2
Arcjet			
1-10 kWe	450-850	0.17-0.23	N_2H_4, NH_3, H_2
10-30 kWe	700-1400	1.0-2.2	
Electrostatic			
Ion Thruster			
1-5 kWe	2000-4000	0.04-0.2	Xe, Kr, Ar
5-20 kWe	2500-6000	0.2-0.6	
Stationary Plasma Thruster (SPT)	800-2500	0.02-0.08	Xe, Kr, Ar
Electromagnetic			
Pulsed Plasma Thruster (PPT)	200-1750	0.000017 - 0.00003	Teflon
Magnetoplasma dynamic (MPD) Thruster	2000-6000	20-100	Ar, H_2

Electric propulsion (EP) has nearly 30 years of space flight experience, during which time thruster designs have matured as improvements based on flight tests and on new technology have been incorporated into operational systems. Nevertheless, EP has so far played only a limited role in military space systems. Technical concerns have included thruster performance, power availability, guidance, navigation, and control (GN&C), and spacecraft interactions. Non-technical issues have included development costs, scheduling, mission constraints at block

changes, and lack of familiarity with the strengths and limitations of EP. Nevertheless, EP makes increasing sense as the size of satellites decreases and technology continues to advance.

Advances in solar-electric power, autonomous GN&C, and electric thruster technology can support an expanded role for EP that will help meet the challenge of new mission applications, including advanced space control techniques. The ability to reposition or reconstitute satellites (without a significant penalty to operational life) is needed by military commanders during quick-response deployments. Past EP flights have focused on low-power thrusters for small velocity-change maneuvers. Today, high-power thrusters and solar arrays offer the enabling technology for large velocity-change maneuvers and orbit raising without the time delays characteristic of past EP systems.

Some initial applications of the electric propulsion concept have been demonstrated in geostationary orbit, where some spacecraft use kilowatt-class arcjets to perform station keeping. This initial application is likely to be replaced by ion engines in the near future. The next payoff would be obtained by using electric propulsion for low-altitude station keeping and attitude control, then extending the technology for transfers from low earth orbit (LEO) to geostationary orbit (GEO) where order-of-magnitude weight savings can be achieved. Again, these orbit transfers would require engines capable of handling tens of kilowatts. Electric propulsion can be used for stationkeeping in a distributed spacecraft systems or to make small continuous random changes in the spacecraft orbit to make spacecraft more difficult to track. Finally, only a small amount of propellant need be reserved to deorbit spacecraft to avoid debris.

The Air Force must fund an aggressive program to develop and demonstrate electric propulsion engines with specific impulse between 2000 and 2500 seconds and power handling capability of greater than 10 kilowatts, as well as basic research into the physics of electric propulsion. This class of engine (coupled with an efficient power generation system) could enable the orbit transfer of a several-thousand-pound spacecraft with significant cost reduction. The coupling of high specific impulse and small size makes electric propulsion an ideal technology for small spacecraft.

Two candidate engine types that should be developed are plasma and ion engines. Plasma engines similar to the stationary plasma thrusters (SPT) or the anode layer thrusters (ALT) developed by the Russians could represent the first stage of development. The most important research to develop these engines will be the material selection. Any material must enable lifetimes of 8,000 hours in components such as high-temperature high-energy-density magnets and cathodes carrying over 100 Amperes of current. Development efforts should include ground testing of these engines (to prove lifetimes of up to 8,000 hours) followed by space testing.

Another unique maneuvering technology that the Air Force should investigate is the use of tethers for momentum transfer. Satellite orbits could be raised or lowered by linking satellites temporarily with a nonconducting line. Although conservation of momentum requires that the total momentum of the system be constant, it is possible to transfer momentum from one part of the system to another (i.e., from one satellite to another) during the time they are attached.

3.8 Evolutionary Technologies for Spacecraft Survivability

During the Cold War, space systems and associated ground systems survivability was a key element of the overall strategy in providing highly survivable command, control,

communications, and intelligence (C^3I) for the forces. With the inception of the Strategic Defense Initiative Organization (SDIO) and its evolution into the Ballistic Missile Defense Organization (BMDO), emphasis on system survivability had increased. In the current BMDO architectures, however, and with the advent of the Theater Missile Defense (TMD), the development of survivability technology for space systems has taken a dramatic downturn. As DoD increases its reliance on the commercial space assets and as other countries develop a capability to negate US space assets, the potential for a Pearl Harbor in space becomes real. The Air Force has to continue to invest in a range of survivability technologies including defenses against electronic warfare (EW), laser, collateral nuclear, high-power microwave, and miniature kinetic kill vehicle (KKV) threats. The range of technologies for survivability includes hardened materials, radiation-hard electronics, anti-jam (AJ) and LPI technologies, and space debris mitigation and protection technologies. There is significant commercial interest in techniques for debris mitigation, and the Air Force should adapt commercial technologies in this area. The Air Force should invest in the development of a threat reporting system that can unambiguously report threats directed at its space assets and take autonomous actions to minimize the consequences.

3.9 Recommendations for Investments in Spacecraft Bus Technologies

The Air Force should follow a carefully targeted plan of investments in spacecraft bus technologies, investing for evolutionary and revolutionary improvements in all facets of spacecraft buses.

3.9.1 Revolutionary Spacecraft Bus Technologies in Which the Air Force Must Invest

Two spacecraft bus technologies offer the possibility of a substantial increase in the exploitation of space by the Air Force, the potential impact of which is so great that the Air Force must invest now. These technologies are:

- High performance maneuvering technologies such as electric propulsion (with thrusts greater than tens of Newtons, at specific impulses of thousands of seconds at near 100% efficiency, the goal for electric propulsion) and tethers for momentum exchange
- Technologies for high power generation (greater than 100 kiloWatts) such as nuclear power, laser power beaming, and electrodynamic tethers

3.9.2 Evolutionary Spacecraft Bus Technologies in Which the Air Force Should Invest

The Air Force should invest not only for revolutionary change, but for evolutionary improvements in performance or reduced life-cycle costs to its systems. The technologies that offer such benefits in the area of spacecraft buses are:

- Structure technologies (e.g., lightweight structures, active vibration suppression, precision deployable structures, and software-controlled multifunctional surfaces)
- Innovative energy storage technologies (e.g., the electromagnetic flywheel battery)

- Attitude control technologies, including attitude sensors and attitude control system (ACS) algorithms
- Radiation hardening technologies for spacecraft electronics
- Low-observable technologies
- Microelectromechanical systems (MEMS) technologies

3.9.3 Commercially Led Spacecraft Bus Technologies

Another set of technologies that will allow for evolutionary change in spacecraft buses will be driven by the commercial sector. These technologies merit minimal investment by the Air Force, yet the Air Force should invest as necessary to adapt these technologies to its needs. These technologies are:

- High-efficiency energy conversion and storage
- Technologies for debris reduction

4.0 Spacecraft Payload Technology

4.1 Introduction

The payload mass fraction of a satellite is that portion of the satellite hardware that performs a useful function (in Air Force terms, communications, reconnaissance, surveillance, etc.). The envisioned 21st century space missions of the Air Force will require advances in four broad categories of payload:

- Spaceborne sensors
- Communications
- Onboard processing
- Weapons

This chapter describes the current status, future Air Force capability needs, and anticipated commercial advances in each of these payload areas, and provides recommendations for an Air Force technology investment strategy.

4.2 Applications of Spaceborne Sensors

Space, as the ultimate high ground, provides a global vantage point for detecting, characterizing, and monitoring targets at and near ground level as well as in space. However, of the many signal modalities (e.g., acoustic, chemical, etc.) that can provide useful information on targets and hostile activity, only electromagnetic radiation can be detected from space. Thus space-based sensor suites will consist of coherent or incoherent electromagnetic wave detectors and arrays of detectors. Specific applications for ground and atmospheric sensing from space include detection and imaging of military activity and assets (including hidden, camouflaged, or subsurface assets), missile warning, detection of weapons fabrication (including nuclear, chemical, and biological weapons), and battle damage assessment. Atmospheric sensing to detect airborne chemical and biological components and to profile atmospheric phenomena such as wind and clouds are also potentially important functions of space-based assets. Other roles include the detection, reconnaissance, and deterrence of hostile space assets, protection of friendly space assets, and the application of force from space. Weather observation, global weather and associated prediction, and the effect of solar activity on the environment in space and its consequences to space systems will continue to be of great interest to the Air Force.

Each application area drives somewhat different performance parameters. The result is requirements that span the electromagnetic spectrum, and include both active and passive approaches. Sensor technologies vary greatly across the electromagnetic spectrum, which can be divided into:

- Microwave and other radio frequencies (RF)
- Infrared (IR)
- Visible
- Ultraviolet (UV)

Historically, active sensors in the RF regime have been termed radar, while active sensors in the IR, Visible, and UV have been termed lidar or ladar. In principal, there is no difference between the operation of active sensors in any wavelength band. Sensor system performance depends not only on sensors, but also on focal-plane technologies, image processing, cryogenic coolers, and optical systems. Needed technology advances in these areas are also discussed in this section.

Over the past decade, the Ballistic Missile Defense Office (BMDO) has been the primary source of funding for sensor development and has been responsible for many of the advances in the visible, IR, and RF regimes. However, this support has been drastically curtailed in recent years, as BMDO's charter has evolved to focus on ground-based systems. The commercial, scientific, and other defense sectors have relied heavily on this funding source in the past and are now facing the prospect of losing this leverage. While some areas with commercial applications will be picked up by industry, many of the performance drivers for defense applications are more difficult and demanding than those for commercial markets. In addition, market forces do not provide incentives for industry to underwrite long-lead-time, high-risk technology developments that lead to breakthroughs in performance, and the science agencies that co-fund these efforts are also experiencing funding cutbacks. Thus DoD funding will continue be required to support high-risk/high-payoff and military-specific sensor technologies. As the arm of the US military with primary responsibility for space, the Air Force must expect to assume the lead in the support of spaceborne sensor development for military applications as they did before the formation of SDIO (BMDO).

4.3 Requirements for Spaceborne Sensors

One of the DoD-unique capabilities is the detection of hostile targets whose position is typically not known in advance, which requires the detection of signatures of small-extent targets within wide fields of view (FOVs). Looking to the future, the ever decreasing size of lethal packages will exacerbate this challenge—significant threats can be brought to bear without massive mobilization of troops or stockpiling of physical assets. The detection of small cross-section targets in a wide FOV is best accomplished with high-efficiency, large-format staring arrays. Scanned systems can cover the same ground area with a smaller array, but only if the detection efficiency is comparably higher, since the dwell time at a given location is shorter. Note that the target can be illuminated by natural sources (e.g., the sun) or by active sources from the satellite (e.g., radar or ladar).

Another challenge for space-based surveillance and reconnaissance is the low contrast presented by many military assets with respect to background, especially when enemy assets are consciously hidden, camouflaged, or placed under foliage or below ground. This drives the DoD to seek more subtle target signatures using an expanded set of measurement parameters, and to fuse information from a variety of different measurement sources (including airborne and in-situ platforms). This translates into a need for detector arrays across wider spectral ranges, and the use of hyperspectral imaging systems (e.g., imaging systems that also provide more than 100 bands of spectral information) operating across this expanded range. For the foreseeable future, Air Force requirements for hyperspectral sensing and data fusion will exceed those in the commercial sector, requiring continued government investment in these areas. Another powerful

approach for detecting low-contrast targets is active sensing. Control of the illuminating source properties (wavelength, phase, and modulation or pulse length) provides additional parameter spaces that aid in target discrimination.

The return of information for military applications is typically more time critical than for most commercial uses. On-demand global knowledge can be achieved only through the deployment of multiple, distributed space platforms. Distributed assets also offer inherent advantages for survivability. Providing this capability at an affordable cost will place stringent constraints on the cost of individual sensor platforms, driving towards significant miniaturization of space sensor systems.

Another important application of spaceborne sensors is in the control of space. This includes the detection, reconnaissance, and negation of hostile space assets, including ballistic missiles, and the protection of friendly space assets, including the sensor platform itself. Sensor requirements for the detection of ballistic missiles depend on where in its trajectory a target is to be detected. During boost phase, the hot effluents render missiles detectable in the visible or near-mid IR, and sensor requirements are similar to those for any small object to be spotted in a wide FOV, as discussed above. Once into cruise phase, detection and tracking of the missile become much more challenging. For space objects in the Earth's shadow, the challenge is to observe a cool or cold object against a dark, cold background, requiring large, sensitive, highly uniform arrays in the long-wavelength IR and beyond operating at very low temperatures. Coast-phase ballistic missiles may also be accompanied by a swarm of decoys, creating additional clutter in the image, and placing even more demanding requirements on sensitivity, uniformity, and sophisticated signal processing.

The application of force from space can take the form of kinetic or beamed weapons. In either case, targets must be identified, weapons aimed or guided, and battle damage assessed. High-precision delivery of kinetic weapons to target will require on-board guidance systems based on either the Global Positioning System (GPS) or optical sensors. Requirements for optical sensor systems are similar to those discussed for ground surveillance and reconnaissance, with the additional need for very rapid response times.

The Sensors Panel has addressed the issue of the global weather observation and the associated sensor development. From a warfighter's perspective, it is necessary to be able to predict weather patterns in the local area up to two weeks ahead. To be able to do this on a global scale, it is necessary to reduce the current cell sizes and develop modeling and simulation technologies that model and predict the weather. Visible and IR sensors recommended in this section of the report will adequately cover these requirements. It will be necessary to develop light weight passive microwave sounders that extend to beyond 200 gigaHertz (GHz).

Solar activity has the potential for degrading the performance of spacecraft by disrupting communications and by causing upsets in unhardened electronics on a spacecraft. Solar storms can cause communication outages in the high-frequency (HF) through ultra-high-frequency (UHF) bands and can cause disruptions at lower frequencies. As DoD's reliance on commercial communication increases, characterizing the solar environment and developing the necessary tools to predict the consequences on terrestrial and space communications will continue to be a demanding technology development area.

4.4 Visible Sensors

One of the earliest military uses of space technology was conducted with visible sensors. Reconnaissance satellites placed high-resolution cameras in space to take photographs of regions of intelligence interest. Although digital image technology has supplanted sending film back from space, the concept of observations in the visible wavelength bands has essentially remained the same.

4.4.1 The State of the Art in Visible Sensors

In the visible range, charge coupled device (CCD) arrays have achieved close to 100% quantum efficiency with excellent readout noise characteristics, in arrays attaining 4k x 4k pixels that can be tiled to create mosaics of even larger effective area. Although this technology currently exists, the entire user community, including DoD and the commercial and scientific sectors, has benefited from extensive DoD investment in this area. With reduced investment from BMDO anticipated in the future, there is considerable concern that the existing infrastructure may erode. Thus continued DoD investment in this area will be required to sustain even the existing capability.

4.4.2 Technologies for Evolutionary Change in Visible Sensors

The performance of CCD arrays is continuing to improve, with development efforts focused primarily on the reduction of readout noise at high readout rates for low signal levels. This capability advance is driven primarily by military surveillance needs. Given the relatively high price of CCD technology, there is limited interest from the consumer market. Within the broader sensor community, there is significant motivation to search for less expensive approaches to achieve large-format, high-efficiency arrays. Array technologies such as the active pixel sensor (APS) that can be manufactured on any standard microelectronics fabrication line are thus of interest to the DoD, since they can reduce the cost of future sensor systems. As an inexpensive technology for commercial electronic camera applications, there is significant industry interest in this area, and the Air Force should watch the development of this technology and adapt it to larger array formats as required. Since the APS architecture utilizes part of the device surface for electronic processing, that portion of the focal plane is necessarily dead. To return full quantum efficiency, and reduce signal processing complexities in target location and identification, defense applications may require the implementation of emerging on-chip microlens array technology that can focus the light on the active portion of each pixel.

4.5 Infrared Sensors

Infrared sensors offer the possibility of obtaining valuable information about an adversary's assets—a broken-down armored vehicle and an operating one may look very similar in the visible, but they have vastly different IR signatures. It is especially important to have high-efficiency IR sensors to detect low-contrast objects against the cold background of space.

4.5.1 The State of the Art in Infrared Sensors

Outside the visible range, commercial interest is less significant, and large sensitive arrays are either very expensive or do not exist at all. In the near-to-mid IR, platinum silicide Schottky

arrays have served as the standard for large-format arrays, available as highly uniform pixel arrays in the 1k x 1k range. However, they do not have high quantum efficiency, and recently indium antinimide (InSb) arrays have replaced them in some applications.

In the long-wavelength infrared (LWIR), the DoD has invested heavily over the last decades in mercury cadmium telluride (MCT) arrays, which represent the current state of the art in terms of sensitivity in the 3-12 μm region. However, this is an inherently difficult material system to work in, and current pixel array size is limited to about 640 x 480. The uniformity for these devices also remains relatively poor, especially at the longer wavelengths.

At wavelengths beyond 15 μm, silicon impurity band conduction (IBC) detectors currently offer the best available sensitivity. To date, array formats are limited to 256 x 256. This technology relies on the growth of ultra-pure bulk silicon, and extensions to larger formats may not be possible for the foreseeable future.

4.5.2 Technologies for Evolutionary Change in Infrared Sensors

Various approaches are being pursued to improve array size and performance in the near-to-mid IR. Modifications to Schottky devices, including spike doping and the incorporation of other silicides, have been shown to extend the response across the mid-IR range. However, the sensitivity of these devices remains relatively low. Meanwhile advances in InSb and indium gallium arsenide (InGaAs) arrays look promising, and large-format arrays with high sensitivity and good uniformity may be available soon in these materials.

Work is also continuing in MCT, albeit at a somewhat reduced level. Given the very large investment in this system to date that has resulted in superb sensitivity, efforts to solve the uniformity limitations through new materials growth techniques seem well focused. Any new LWIR technology must be compared to anticipated MCT characteristics for a realistic assessment of its potential. One of the most promising new technologies emerging over the next few years is the silicon- and gallium-arsenide-based quantum well infrared photodetector (QWIP) technology. QWIPs offer large-format IR arrays operating out to 15 μm and beyond (i.e., beyond the practicable range of MCT). Array formats as large as 256 x 256 with a spectral peak as long as 15 μm have already been demonstrated, and array sizes exceeding MCT at all wavelengths are expected within a year or two. In comparison to MCT, QWIP technologies also offer superior uniformity and are expected to achieve greater D* values when operated at very low temperatures. They are also much easier to fabricate, which should make them much less expensive. QWIP technology offers another valuable capability—because the spectral response bands can be made fairly narrow, it is possible to achieve simultaneous imaging in multiple spectral bands by stacking multiple layers of stepped spectral response. This effectively provides three-dimensional, hyperspectral data in a staring mode. Since there is limited commercial market for cooled LWIR arrays, and because this is a key capability for future space surveillance needs, the DoD should continue to develop QWIP technology and explore its potential for a broad range of defense applications.

To exploit the full capability of QWIP technology for detecting weak or low-contrast signals, low-temperature readout electronics will also be required. Standard complementary metal oxide semiconductor (CMOS) readout electronics freeze out at temperatures below about 60 K. Thermally isolating the sensors from the electronics is cumbersome at best, and precludes the

use of large two-dimensional imaging arrays. Gallium-arsenide and germanium-based electronics are emerging that can meet this need. As there are few, if any, commercial drivers for low-temperature imaging arrays; the DoD will need to support the development of low-temperature focal-plane electronics.

Ultimately, intrinsic detectors offer important advantages for imaging of fast-moving, dim space objects, due to their inherently higher quantum efficiencies. Intrinsic technologies under study to achieve high quantum efficiencies at very long wavelengths include new low-bandgap materials and novel, artificially structured superlattice materials. The former will require significant investment in new optoelectronic materials systems, possibly comparable to the MCT investment. Artificial superlattice structures offer the potential to achieve the desired capabilities in more tractable materials systems, but will require significant development in the control of atomic-scale deposition of strained-layer structures. The maturity of these approaches is still quite low, and with limited commercial drivers, these technologies will require extended support from the DoD community to achieve the desired capabilities.

In general, the detection of weak or low-contrast IR signals beyond a few microns requires active cooling of the detector to reduce the dark current noise below signal levels. To date there has been little commercial incentive for the development of such coolers, and DoD investment will need to be continued. High-resolution imaging also requires very accurate and stable pointing. Mechanical coolers present a particular challenge in this regard, and vibration-free coolers or active vibration suppression technologies remain an exclusive requirement of the government. Candidate vibration-free technologies include sorption refrigerators and high-speed turbo-Brayton systems. Both have demonstrated technical feasibility in the laboratory, but require further engineering development and life testing for flight viability.

4.6 Ultraviolet Sensors

An ultraviolet detection capability is valuable for missile warning, especially for high-altitude and through-cloud tracking. UV imaging is also valuable in discriminating the hard body from the plume in boost-phase ballistic missile negation.

4.6.1 The State of the Art in Ultraviolet Sensors

Most state-of-the-art detectors for the UV region depend on photoemission from special cathodes such as cesium iodide (CsI) and cesium telluride (CsTe). These are incorporated into photomultipliers used at the input of microchannel plate (MCP) imaging intensifiers at the focal plane, with readout following visible wavelength imaging of the multiplied photoelectrons from the MCP with a conventional visible-light-sensitive CCD. Both one- and two-dimensional arrays are used. The quantum efficiency for the photocathode itself is in the range of 10-20%.

4.6.2 Technologies for Evolutionary Change in Ultraviolet Sensors

Current DoD technology investments to achieve the desired large array formats in the UV include the development of wideband sensor materials, innovative design changes in existing large-format visible arrays (such as delta-doped CCDs), and the use of high-work-function photocathodes such as aluminum gallium nitrate (AlGaN). High-work-function photocathodes

offer the potential of truly solar-blind detection without additional filters and tailorable sensitivity thresholds across the UV region of the spectrum, as well as being inherently radiation-hard. However, considerable materials development will be required before these technologies reach maturity. For the near term, modifications of existing visible array technologies will need to be implemented. Since there is little commercial push in the UV, DoD investment will need to continue.

4.7 Radar

Active sensing can, in principle, be carried out at any wavelength. Rather than simply gathering at wavelengths that an object reflects from the sun or emits due to its temperature, it is possible to illuminate an object with radiation and sense its return signal. The resolution in both space and time that one can achieve is determined by such fundamental parameters as the aperture size of the system and the transmitter power.

4.7.1 The State of the Art in Spaceborne Radar

To date, radio, microwave, and IR frequencies have the most value for defense active sensing applications. Space-based radars can be particularly powerful as all-weather, day/night detection, tracking, or imaging systems. Space radars can be implemented either in high-resolution imaging synthetic aperture radar (SAR) or low-resolution moving target indicator (MTI) mode. For SAR, the power required is a function of both the resolution and coverage, and due to on-orbit power limitations, high-resolution SAR has been implemented only in systems with relatively narrow fields of view. Broad-area MTI systems have also not been implemented in the US. Such systems would contribute significantly to the all-weather global awareness missions, but are costly with today's technology.

4.7.2 Technologies for Evolutionary Change in Spaceborne Radar

In addition to on-orbit power, the keys to achieving practicable systems in the future are efficient RF modules, electronically steered phased arrays, and low-mass antenna structures. Both SAR and MTI systems require these advances, but the performance requirements for global-coverage wide-area MTI systems are even more demanding than those for SAR. Current solid-state RF transmitters achieve only about 40-45% efficiency, while a goal of 70-75% is reasonable within 5-10 years. Transmitter power is also limited by the power capability of individual solid-state devices, which can be overcome by moving to phased arrays in which the power load is distributed across the array. Phased-array technology also permits electronic beam scanning. Assuming adequate transmitter power and data handling capabilities, vertical resolution scales with the bandwidth, which can typically be extended to only approximately 10% of the carrier frequency, driving towards higher system frequencies. However, higher frequency signals are also more strongly absorbed by the atmosphere, calling for even higher transmitter powers. The receiver antennas must have large, high-precision surfaces for efficiency and accuracy. Advances in precision deployable structures and other "membrane" approaches offer great reduction in launch mass and dimensions. Since the DoD resolution and coverage requirements are more demanding than those for commercial applications, there is insufficient incentive within the commercial sector to provide the required technology development in these areas.

4.8 Lidar (Ladar)

Spaceborne lidars enable additional measurements of the near-ground environment such as the detection of chemical and biochemical signatures associated with weapons fabrication and height profiling of wind speed and direction. Enhanced target information can be obtained through a wider range of source wavelengths and through the analysis of the time response of signals stimulated by pulsed illumination. Short-pulse lidar can provide highly accurate target ranging, which is useful for track generation, and can even generate a range profile of a target, which is useful for target identification. Spaceborne lidars enable additional measurements of the near-ground and atmospheric environment. Using tunable, narrow-band sources, they can detect specific chemical and biochemical signatures associated with weapons manufacturing. They can also provide accurate height profiling of atmospheric parameters such as pressure, temperature, humidity, wind speed and direction, and return profile information on airborne aerosols and clouds. In general, the analysis of spectral and temporal characteristics of the returned signal can provide enhanced information over that obtained passively with solar illumination alone.

4.8.1 The State of the Art in Spaceborne Lidar

Airborne lidar systems have been fielded at wavelengths from the near IR (0.8 micron) to the LWIR (10.6 micron), but to date a full-up spaceborne system has not been implemented due to the large size and power requirements of current systems. The challenge for active sensing at any wavelength is the weakness of the returned signal, which must be compensated by high-power sources. Thus efficient, high-power laser sources and sensitive, discriminating detectors and arrays are critical technologies for reducing the system mass. A recent NASA shuttle experiment demonstrated some of the emerging light weighting technologies in a three-frequency, incoherent backscatter lidar measurement of cloud tops.

4.8.2 Technologies for Evolutionary Change in Spaceborne Lidar

Laser sources are needed across the visible and IR ranges, and extension into the UV may also be valuable in the future. Visible and near-IR diode lasers with over 80% wall-plug efficiencies have been demonstrated in the laboratory, but have yet to be fully validated in space. The fiber optics market has driven and will continue to provide incentive for the development of moderate-power near-IR diode lasers at specific fiber-optic wavelengths. However, the extension of the commercially developed capabilities to those required for space-based defense applications has been supported primarily by DoD. Defense requirements include higher powers, wider spectral ranges, and tunable, single-frequency operation. This support must be continued, as no commercial drivers are on the horizon. Low-mass optical benches and holographic reconstruction techniques can also lower the system cost by reducing the system mass. Commercial advances in these areas are not likely in the near term, and thus continued DoD investment will be required.

4.9 Evolutionary Technologies for Sensor System Miniaturization

Sensors for spacecraft use, whatever their wavelength of operation, become more useful as they are made smaller and lighter. The anticipated paradigm shift to clusters of small satellites to perform military global sensing tasks will provide an unprecedented incentive to miniaturize

sensor systems. To date, BMDO sensor development for the Brilliant Eyes system has placed the greatest demands on the size of a space-based imaging system.

An emerging technology of great potential for miniaturizing sensor systems is microelectromechanical systems (MEMS). MEMS is the next step in the microelectronics revolution, in which multiple functions are integrated on-chip. Applications include chip-level transducers, light sources, fixed and adaptive optics, and on-chip integration of these functions with microelectronic control and processing capabilities. Some aspects of MEMS are being addressed by the commercial sector, and rapid advancement is expected. The Air Force should monitor these advances, and adapt as required. One area not as likely to see commercial focus is on-chip optics, which should be supported by the Air Force with space-based sensing and autonomous maneuvers as the requirements drivers.

Technologies that lower the power required for sensor systems can also translate directly into mass (and thus into cost) savings. For example, emerging technologies that combine sensor and processing capability on the focal plane, such as the active pixel sensor, offer orders of magnitude reduction in sensor power, simplified control electronics, and performance advantages such as agile readout capabilities, as well as the reduced cost of large arrays noted earlier. Low-power, next-generation smart sensors should be explored for Air Force benefits, and supported where commercial markets do not provide adequate development incentive. IR array technologies that do not require active cooling, such as bolometers or tunnel sensors, also lower the system power requirements, and will be valuable for long-wavelength IR spaceborne systems that do not require the highest sensitivity, and for extending the detection range across the far IR where quantum detectors do not exist.

Technologies must also be developed to reduce the mass of optics required to achieve high resolution and/or to detect weak signals. High resolution alone does not require large collection areas, and can be achieved with sparse, distributed, or synthetic apertures. In the future, distributed apertures may consist of individual spacecraft forming a coherent, configuration-controlled cluster. Such schemes will require advances in autonomy and inter-spacecraft communications links. The large collection area required for the collection of weak signals can be addressed with "membrane" structures such as deployables or inflatables, which offer large-surface-area reflectors with low mass. However, requirements for surface conformation and precision alignment drive additional technology advances. Adaptive optics can be used to correct for the less-than-perfect optical surface of such structures, and MEMS precision actuators are expected to be fundamental to both conformation and alignment control. Smart focal planes and MEMS-based high-rate adaptive zoom optics also offer important capabilities for agile automatic target recognition (ATR) and tracking. By rapidly reconfiguring the optics and/or active pixels, it will be possible to focus attention on the interesting portion of the image, and monitor it at increased speed.

4.10 Revolutionary Technologies for Satellite Clusters

The development of low-cost, single-function satellites offers new horizons for space applications when the satellites operate cooperatively either in clusters (local formations of satellites) or in constellations (satellites distributed both within an orbital plane and over a set of orbital planes). The vision of what can be achieved from space is no longer bound by what an individual satellite can accomplish. Rather, the functionality is spread over a number of

cooperating satellites. Further, these distributed systems of satellites allow the possibility of selective upgrading as new capabilities become available in satellite technology.

The analysis in the Space Applications Panel report shows that while distributed systems do not provide a cost effective answer for all applications, there are many applications for which small sensors on many satellites scale very well and give cost-effective solutions. As an example, passive scanning imagers on dedicated satellites or communication constellations scale very well indeed. In addition, distributed systems have distinct advantages in survivability. This results from the distribution of capability over all the components. Individual satellites, once found and tracked, can be easily destroyed from the ground by high energy lasers or by kinetic kill vehicles. Distributed systems will degrade in proportion to the number of satellites lost. The flexible and proper interconnection of the rest will make the overall system intrinsically survivable. Thus the Space Applications Panel report finds that advances in computers, sensors, and materials will permit establishment of large constellations of interlinked satellites, whose integrated output will give global, real-time coverage. Reducing range to target and constellation altitude reduces satellite size and cost of coverage. The advantages of such systems have already been embraced by the commercial space industry. The Space Applications Panel report makes the following recommendations:

- The Air Force should create a road map that recognizes that the twin realities of inexpensive, single-sensor small satellites and distributed processing and communications will enable a significant advance in reconnaissance, surveillance and battle awareness
- The Air Force should begin development of a suite of small satellites to complement the evolving national sensors for timely battle field reconnaissance
- The Air Force should focus, where appropriate, on hybridized, distributed architectures, employing on-board processing, storage, and cross-linking now being incorporated in commercial distributed space system designs

The development of Global Awareness will require an array of collectors with all weather sensing. For example, frequent revisit SAR of mid to low latitudes with one meter resolution could be achieved by a small constellation of low-inclination, low-altitude small satellites. These would provide all-weather, day/night observation capability. In addition, one-meter mid-wavelength infrared, two-meter long-wavelength infrared, and two-meter multispectral data could be provided by a constellation of single-purpose small satellites. The Sensors Panel recommends the possible use of bistatic SAR in which a microwave illuminator is placed in a synchronous orbit with lower orbiting receivers or airborne receivers is an interesting alternative and describes a low-cost space-based surveillance concept involving the use of approximately 10 to 20 low-earth-orbiting satellites for SAR coverage of a theater.

One of the revolutionary effects of the technologies that enable clusters of cooperating satellites will be the ability to flexibly form extremely large (in wavelengths) coherent apertures in space for sensing, communications and weapons. The development path to clusters begins with systems of interconnected, cooperating satellites such as Iridium or Teledesic whose constellations will distribute functions across their orbiting networks to provide global communications. The applications path to coherent clusters of satellites goes through sparse distributed aperture sensing satellites. The mission need driving the technology is the need to

continuously sense the target and background environment in an area of interest. To provide continuous viewing opportunity over arbitrary spots on the globe requires constellations on the order of a hundred satellites (depending on the viewing angle constraints) at altitudes on the order of a thousand kilometers. At altitudes on the order of ten thousand kilometers the number of apertures shrinks to the order of ten to twenty. At geostationary altitude the number of apertures reduces to the order of three to ten depending on the need for high latitude coverage. For imaging applications the aperture dimension required to maintain resolution scales directly with the distance to the target. However, the aperture may need to be only sparsely filled where the energy received is not the limit, e.g., with illumination from the sun. At low altitudes a monolithic aperture may be reasonable. At moderate altitudes a sparse, distributed aperture on a deployable structure may provide equivalent performance. At higher altitudes, a cluster of cooperating satellites flying in formation can form the aperture dimensions required without the weight and cost penalty of a satellite subtending the entire aperture. The requirement on the cluster elements is to maintain autonomously relative positioning, attitude, and communication among the elements of sufficient quality to allow the aggregate to maintain phase coherence over the aperture. The distributed system then becomes a constellation of clusters.

The same technologies for clusters of cooperating satellites for passive sensing will enable revolutionary change in active systems for sensing, communications, and weapons. For active apertures for sensors, communications or weapons the aperture may be thinned but not sparse to the degree that the power (and waste heat) radiated per element is too high. Instead of a relatively small number of cooperating elements in a cluster, these applications will drive towards large numbers of identical cooperating (perhaps docked) elements that permit significant economies of scale in manufacturing and flexibility in launch. An example application of this approach is an alternative path to the frugal Global Precision Optical Weapon (GPOW) space-based laser. Rather than large monolithic flexible optics directing the beam from a single large laser powered by 10% efficient solar-to-chemical energy collection/storage and 25% efficient laser conversion, a clustered approach would employ phased diode lasers (like the Fotofighter concept) with 50 to 90% efficient laser conversion and 20% to 30% solar electric energy collection. This approach can also be applied to the generation of very intense RF beams from a set of separate elements on different satellites with the precision station keeping to enable all elements to radiate coherently. Such an intense RF beam could be used to overcome local jamming or to burn out sensitive electronics.

Thus, revolutionary capabilities will be enabled by the use of distributed systems and the Air Force must invest in the technologies for clusters and constellations of cooperating satellites (e.g., high-precision stationkeeping, autonomous satellite operations, very high performance communication links, distributed processing, and signal processing for sparse apertures).

4.11 Applications of Spaceborne Communications

Communications are vital to United States defense posture and operations. It is essential to providing the Air Force with an assured, on-demand, real-time virtual global presence and a mechanism for the delivery of Knowledge on Demand. To achieve this affordably, full use must be made of commercial communications assets and technology while at the same time recognizing and investing in those technologies that are necessary to meet DoD-unique needs even in a hostile environment.

The combined DoD and commercial assets must provide world-wide connectivity, allowing instant contact between CONUS and rapidly developing theater operations. Connectivity must be provided for timely high-data-rate information collection, relay, and dissemination to the war fighter at all command levels. Connectivity within the theater between many disparate communications systems must be established to make use of the investment in legacy systems until they are replaced by new communications systems with connectivity built in. There is a paradigm shift occurring in communications from dedicated, circuit-switched connectivity to packetized, access-on-demand connectivity for both voice and data; this is most apparent in the commercial world in the adoption of asynchronous transfer mode (ATM) communications, but it is clear that packetized communication networks should also be used by the military to maximize traffic that can be handled by available transmission circuits of all kinds, satellite and ground-based.

In designing a DoD communications architecture, it is necessary to recognize critical differences between commercial and military needs. Military communications must have the ability to prioritize traffic to provide assured, timely transmission of mission-critical information. This means that some core, protected capacity must be provided that is robust to circuit outages from either technical problems or intentional disruption. Less-critical traffic, which is the bulk of the communications load, can be moved over commercial or commercial-like systems. Military end-users are frequently at mobile sites or where access to fixed communications assets is not available. These users are frequently in-theater, and have the highest demand for time-urgent, mission-critical communications connectivity (but not for capacity) even under direct attack by an enemy. These differences drive the technology needs for military communications systems and therefore the investments that must be made to provide service not available or adaptable from commercial systems.

4.12 Requirements for Spaceborne Communications

Satellites are a particularly useful platform for communications payloads. Their primary advantage is connectivity over long ranges (particularly oceans) and to users not connected to other long-haul circuits (e.g., mobile users). Today, the primary use of commercial satellite communications is long-haul point-to-point trunking among large, fixed ground sites. These circuits can be (and are) used (leased) to provide bulk connectivity for the military. This practice should be continued and expanded as much as possible, along with use of other commercial long-haul circuits (e.g., fiber). New commercial satellite services are providing connectivity to end users; examples include Iridium, Direct Broadcast Service (DBS) TV, and INMARSAT. These systems can be used by the military where prudent, but their limitations (in assured availability and robust connectivity) should be recognized. However, the technology that has been developed for these new systems is available for inclusion in DoD-specific satellite communications systems; such systems using available technology could be bought outright by DoD or their use acquired through leasing service on orbit (as has been done with LEASAT). Only when technology that is not in the commercial domain is required is development and procurement of satellite systems by traditional government contract warranted. Satellites that provide the core, protected capacity (such as MILSTAR) are examples; satellites that collect intelligence information and relay it are other examples. The complete architecture for military ground and space communications must include service for both core/protected needs and routine

support needs, making use of appropriate types of circuits for each need and allowing traffic to flow among the various circuit providers seamlessly.

In summary, commercial communications (satellite and terrestrial) can provide much of needed military communications for:

- Data, voice, and image transmission among fixed sites in CONUS and world-wide
- Routine traffic among some mobile users (ships, aircraft, vehicles)

However, military-specific communications requirements will need military-specific solutions for:

- Timely relay and dissemination of high-volume intelligence information from sensors to warfighters
- Robustness against interference (jamming) and tampering (information warfare) on critical circuits
- Instant establishment of volume service in remote areas, particularly to forces on the move

4.13 Spaceborne Communications Technologies

Historically, communications with satellites have been provided by RF links. There is room for significant improvement in this technology area, although moving into the optical band of the electromagnetic spectrum offers considerable advantages to the military user, especially as requirements for bandwidth increase.

4.13.1 The State of the Art in Spaceborne Communications

Today's military satellite communications are provided by three DoD dedicated satellite systems plus much leased commercial point-to-point trunking. These three systems (in increasing robustness of service) are ultra-high-frequency (UHF) service (provided by FLTSAT and leased UHF satellites) for simple, low-rate, low capacity mobile terminals; super-high-frequency (SHF) service (provided by DSCS) for high-volume, long-haul trunking from large, fixed terminals and for modest sized terminals on ships and in ground forces at higher echelons; and extra-high-frequency (EHF) service (provided by MILSTAR and its FLTSAT EHF Package precursors) for low-volume, highly protected service to Single Integrated Operations Plan (SIOP) forces and other highly valued platforms, including mobile users on ships and aircraft.

The UHF system is highly desired by mobile users and is extremely useful, but is grossly oversubscribed in times of stress; it is also very vulnerable to interference from even small sources. This frequency band is very desirable to mobile users because the terminals and (particularly) antennas are small. There has been a large investment in military UHF satellite communications terminals that work at the allocated frequencies within the military UHF band. All Navy ships are so equipped, many Army terminals exist, and most large Air Force planes have UHF satellite communications capability. The technology for UHF transponder satellite service is well known by industry. This class of service is available through leasing of service

from industry. A similar class of service will be offered by commercial carriers through low-altitude constellations operating around 1 GHz. The DoD should determine the suitability of these commercial services as an eventual replacement for current UHF military satellite communications systems. Issues to be evaluated include transmission costs, acquisition of new terminals to replace current inventory, and guaranteed world-wide service.

The DSCS system (operating in the allocated military band at 7/8 GHz) is used mainly for trunking of high-volume data between CONUS and overseas sites through large, fixed terminals which have protection against jamming through bandspreading and commanded antenna pattern control (although lower data rates may be necessary under jamming). DSCS is also used to provide communications to Navy ships for C^3 and for general traffic; this is the Navy's only current assured satellite communications connectivity. DSCS is also used by the Army through transportable terminals for connectivity at higher echelons between the Army Mobile Subscriber Equipment (MSE) in-theater trunking system and CONUS. A significant investment has been made in SHF terminals by these users. Some more-mobile Army terminals are starting to be employed at lower echelons to maintain connectivity between elements that are not within the line-of-sight required by the MSE equipment, but rapid transport to theater is a problem (inadequate airlift) and ability to keep up with rapidly maneuvering mechanized forces is a serious shortcoming. Future use of the SHF band by the military is appropriate to take advantage of the ground infrastructure investment (terminals) and the frequency allocations owned by the military.

Assured frequency allocation is a major issue in military satellite communications. (It should be noted that the SHF allocation is only 500 megaHertz (MHz) wide and individual transponders on DSCS are narrower than that, limiting the maximum data rate for some users to far less than desired.) Since the only DoD-specific technology on DSCS is secure telemetry, tracking, and control (TT&C) and reconfigurable multi-beam antenna systems, it seems likely that such future services could be provided by spacecraft acquired through commercial-like contracts. Alternatively, service could be provided through commercial satellites operating in the commercial bands of 4/6 GHz and/or 11/13 GHz, although antenna discrimination adjusted in real time to fit a battlefield situation will not likely be available this way. Substantial numbers of new military terminals will have to be procured to operate at these frequencies. The Army is currently developing the STAR-T tri-band terminal for the Ground Mobile Forces that will operate at both commercial bands as well as the military SHF band. Use of commercial satellites for war fighting situations will require transponder assignments by the satellite owners and use approvals of the country involved; this may present some delicate political issues that impact on the military need for assured access to communications.

MILSTAR is just coming online and represents a quantum leap in assured, anti-jam (AJ) service to highly valued platforms. Although initially designed for SIOP forces, it is able to provide any small, mobile EHF (44 GHz uplink, 20 GHz downlink) terminal with very high-quality, extremely AJ service. A current drawback is limited capacity per terminal of 9600 bps. This capacity problem is being addressed in the MILSTAR II spacecraft, which will be launched in the next few years; protected capacity of up to 1.5 Mbps per terminal will be available. The Navy and the Army have made substantial commitments to procurement of MILSTAR terminals; the smaller antennas of the EHF terminals (vs. SHF) are an advantage to both of these user

communities from platform installation and mobility considerations and do not require sacrifice of AJ capability. MILSTAR satellite communications technology is uniquely DoD; it includes the most aggressive use of on-board signal processing for AJ and for demand-assigned, circuit-switched routing (but not packet routing). MILSTAR uses on-board processing for jamming protection through frequency-hopping/dehopping and through antenna pattern shaping (but not yet for real-time adaptive jammer nulling). Future acquisition of this class of service should be done through the regular DoD procurement process because of these unique technologies for jamming protection that are not of interest to the commercial world.

In comparing future communications needs with current capabilities, clearly there are service deficiencies:

- The ability to quickly provide very robust (AJ) service to small terminals that can be carried and operated on the move by forces is extremely limited.
- Very high-rate (many gigabits per second or Gbps) relay of intelligence data is not available through any current system, particularly from airborne platforms or sensor spacecraft. There is current interest in the use of commercial DBS technology to provide about 22 megabits per second (Mbps) for relay of intelligence data from a central injection station to tactical users in a theater of operations using low-cost derivatives of the commercial DBS TV terminal. There is an architectural issue in this concept, in that this data could also be relayed through existing military communication satellites and terminals. Also, this DBS capability does not address the needs for very high-rate (many Gbps) intelligence data relay from sensors to analysis sites.

To solve these DoD-specific problems and to provide these services using lower-weight and lower-power (and hence lower-cost) satellites will require technology investments by the DoD.

4.13.2 Technologies for Evolutionary Change in Spaceborne Communications

The Air Force should invest in those satellite communications technologies unavailable in the commercial sector that are critical for military-specific, core communications services; other technologies and services can be adapted from commercial practice. From the foregoing discussion these critical technologies are:

- Antenna systems that efficiently direct downlink power to users (even at unplanned locations) and reject jamming on the uplinks by use of multi-beam, real-time adaptive antenna patterns
- Very high-rate (many gigabits per second) communications for sensor data relay and dissemination among spacecraft, airplanes, and ground sites; optical communications is the method of choice
- Onboard processing for jamming protection that despreads and demodulates uplink signals and routes them to appropriate downlinks, providing interconnection of disparate users (including packet communications)

The present state of practice for advanced antenna arrays is to use global spot multibeam routing and switching. However, recent advances on antenna arrays have provided limited adaptive beam forming. Based on the present development, a 3 Gbps data throughput rate should be achievable on satellites before the end of the century. It will be necessary to continue shifting the RF communication band to a higher frequency with wider bandwidth to obtain increased data rates. Therefore, it is essential to continue to develop the electronics required to send telemetry at a higher operating frequency.

The use of *real-time adaptive* beam patterns on up-link and down-link on communications satellites has been very limited. Today, commercial satellites have multiple beams, but they are usually fixed in anticipation of a particular orbital location and an intended customer base. For military communications, neither of these is likely since the theater of operations is scenario-dependent. The ability to create multiple narrow-beam downlinks allows the satellite transmitter power to be directed only to the intended users, as well as permitting frequency re-use (important in the crowded spectrum allocations). Both factors result in increased capacity through the satellite. The ability to create multiple narrow-beam uplinks provides high receiving gain that in turn allows either smaller earth terminals to close the link or higher data rates to be transmitted. Substantial reductions in ground terminal costs will result. More importantly, narrow-beam uplinks can be used to reject interfering sources (jammers) out-of-beam, and, through combining of multiple beams, to reject jamming sources *within* a beamwidth. The ability to do such real-time adaptive antenna beam formation to create very deep, narrow nulls anywhere within the field of view of the satellite over the very wide bandwidths necessary for AJ modulation is not something that the commercial sector will develop (commercial users are interested in out-of-beam signal reduction for frequency re-use, a much easier problem); the technology for this military capability must be developed through Air Force investment. This technology is necessary to meet the military requirement for robust, AJ service (particularly for mobile users with modest size terminals) in remote areas with little warning. The beginning of the application of this technology has been seen in MILSTAR, but substantial improvements in performance and in reduction of weight and cost are certain with continued investment. The specific technologies in which the Air Force must invest include:

- Use of optical phase control and combining to maximize nulling depth over bandwidths consistent with AJ spreading (GHz) while minimizing system weight
- Use of optical phase shifting to drive each element in a phased array antenna through a fiber, to avoid heavy ferrite phase shifters, heavy waveguide feeds, and difficult integration problems

For a fixed operating frequency, as both range and desired data rates for communication increase, one is faced with increased transmitter and antenna sizes as well as limits on allocated frequency bands. It is for these reasons that historically satellite communications have pushed to ever higher frequencies, where the same size antenna concentrates the transmitted energy into a narrower beam and where wider frequency allocations are available. Frequencies now in use go as high as 60 GHz, and expansion to the 95 GHz band should be pursued for the future. But even at these millimeter wave frequencies, multi-Gbps data rates require unreasonably large and heavy equipment over geostationary ranges. It is for this reason that optical communications systems have generated so much interest.

Optical frequencies offer the ability to communicate at very high data rates (many Gbps) over long ranges (crosslink at synchronous orbit or from aircraft to synchronous orbit) using small apertures (10 inch telescope) and low laser power (a few watts). Bandwidth for these high data rates is not available easily in conventional RF bands, and RF antennas would be considerably larger than optical telescopes, leading to weight and integration problems on spacecraft and aircraft. The extremely narrow optical beamwidths utilized (a few microradians) require special techniques for acquisition and tracking. These problems have been the primary stumbling block to use of laser communications in the past, along with reliability of the laser sources. However, continued investment by the Air Force will result in the ability to successfully field such systems after the year 2000, when the next generation of military communications satellites must be procured, and will be essential to relay of the volume of sensor traffic that will appear due to global surveillance developments. Optical links will also have application to uplinking data from airborne sensors, in addition to spaceborne sensors, to high-orbit relay spacecraft; the small optical link can be more easily integrated on an aircraft. (For example, the Tier 2+ unmanned air vehicle (UAV) will utilize a four-foot diameter satellite antenna to uplink its SAR and electro-optical (EO) sensor data even at modest data rates; the integration of this antenna had a major impact on airframe design.) The technology for optical links of this nature will not be developed by the commercial sector because the data-rates and required optical beamwidths needed are considerably more difficult to implement than the short-range, modest-rate optical crosslinks that may be used by some of the proposed commercial distributed-satellite offerings; the Air Force must make this technology investment. Specifically, the optical communications technologies in which the Air Force must invest include:

- Long-life, diffraction-limited, multi-watt laser sources
- Efficient multi-Gbps modulation techniques with forward error-correcting codes
- Efficient, near-quantum-limited optical demodulators
- High-bandwidth steering mirrors for acquisition and tracking
- Wavelength-division multiplexing techniques that efficiently combine several-watt laser transmitters operating at different laser wavelengths (as opposed to lossy combiners that suffice for commercial fiber systems)

On-board signal processing is essential to provide full AJ capability when uplink signals are spread over very wide bandwidths, as they are in the MILSTAR system. Once uplink signals are de-spread and channel assignments de-randomized, the ability to demodulate an uplink transmission into digital data and route it to an appropriate downlink will provide efficient utilization of satellite resources (in particular, downlink power) to allow volume service into remote areas for theater operations. Processing will be used again on the downlink to form a time-domain multiplexed (TDM) data stream of all traffic with randomized time slot assignments after which frequency-spreading will be applied; both operations are needed to provide downlink jamming protection. The on-board processing that is necessary to implement AJ is not the same as on-board processing for message routing alone that is being planned by some of the commercial satellite services such as Iridium.

As antenna systems become more capable, the benefits of on-board demodulation/remodulation will increase. Not only will downlink resources be utilized more efficiently by

routing to only the appropriate downlink beam, but the modulation format change possible in the satellite will be able to be used to interconnect disparate ground-based terminals. On-board processing may also be used to establish a packetized data network through the satellite. By reading headers on packets, it will be possible to dynamically switch data to the appropriate downlink beam, the appropriate modulation format, and the appropriate data rate for the intended recipient. This will allow the satellite resources to be allocated on a packet-by-packet basis, rather than, for example, the circuit-switched paradigm used by current-generation MILSTAR, resulting in a greatly increased communications efficiency. This capability will be a necessary part of the current efforts in digitization of the battlefield. Such on-board signal processing will become possible with the increased capability of specialized digital processing chips that will be developed over the next decade by the commercial market. However, Air Force investment to adapt the use of these chips to the satellite communications is required. The Air Force must also take the lead in the adaptation of commercial network and signaling protocols to address the robustness needs of core services while providing transparent flow of data through multiple network nodes, whether they are in space or on the ground.

4.14 Applications of Spaceborne Information Processing

Information processing and extraction will be critical functions in the next generation of satellites. In order to make the information gathered by a spaceborne surveillance or reconnaissance system useful to the warfighter, the Air Force needs technologies to perform two related but distinct functions:

- Storing, moving, and analyzing vast amounts of data
- Extracting knowledge from the above data set

4.15 Requirements for Spaceborne Information Processing

Current projections of the data being delivered from imaging satellites show that data rates greater than one terabyte per day will soon be required. Such rates will stress communication links and memory, and will be difficult to sustain in a cost-effective, secure manner. Furthermore, the sheer magnitude of the data will inhibit rapid information extraction needed in time of conflict. To be effective, on-board satellite information extraction will be required. Fortunately, a great deal of progress is being made in information processing for communication systems and computer vision by commercial and industrial laboratories at this time. The commercial sector is pioneering certain types of image processing, coding, compression, and very large scale integration (VLSI) architectures for video and telecommunication applications. The Air Force can effectively adapt much of this technology where needed as it develops in the next decade. Air Force investment will, however, be required in the area of sensor fusion as the next generation of satellites develops multidimensional sensing (radar, passive observation, hyperspectral, lidar). Furthermore, DoD should take the lead in developing with commercial industry standards for information retrieval and processing while such techniques are still in a nascent phase.

4.16 Spaceborne Information Processing Technologies

Information processing technologies include not only the hardware for storing and processing large amounts of data, but protocols, techniques, and algorithms as well. As the

amount of information available increases, such techniques as artificial intelligence and neural networks will play an increasingly important role in fusing data into a complete picture of the battlespace and extracting knowledge from this picture for use by the warfighter.

4.16.1 The State of the Art in Spaceborne Information Processing

The Information Age has led to the creation of a major commercial market and research effort in information processing. The major US national labs (e.g., ATT Bell Labs, IBM) are establishing significant research efforts in information processing for data and telecommunication. There are also significant international efforts in this area (primarily in Japan) due to the large market for information transmission. The commercial information industry has pioneered data compression, improved bandwidth utilization, and established communication protocols for connecting different points on a vast network. Image compression algorithms such as JPEG and MPEG allow video data to be transmitted with reduced bandwidth. However, they have been designed to take advantage of frailties of human vision, and are not adequate for the image processing required for military applications such as target recognition. The Air Force and DoD should work with industry to develop standards for high definition image compression and processing formats so that future industry-driven developments will benefit military applications.

Other significant commercial developments include dramatic increases in computing power. Today it is possible to acquire single board processors with 250 megaflop (Mflop) performance. By 2010 it is expected that for approximately the same investment 20 gigaflop (Gflop) performance will be available that will consume approximately the same power as the processors used today. Data storage is increasing rapidly and predictably. Terabyte storage will be available in hard disk and random access memory (RAM) form for these processors. The Air Force should adapt these technologies to suit specific tasks.

4.16.2 Technologies for Evolutionary Change in Spaceborne Information Processing

Effective utilization of space will require on-demand knowledge extraction using sensor data in multiple dimensions. Hyperspectral data, in conjunction with SAR or optical images, will be needed, and will require significant data processing, storage, and data basing. Automatic target recognition (ATR) is a unique DoD task. While computation should be done where it makes more sense, processing of data on-board the satellite will be desired for many applications. For example, the parallel nature of optical imagery from a focal plane array can best be processed by a massively parallel processor directly connected to the array. Serializing optical imagery data for transmission to an earth station for processing introduces delays and errors and stresses communication channels. Commercial industry will continue to lead the development of advanced processing technology on the ground. The Air Force must invest in technologies to leverage commercial developments and to adapt these to the unique space environments and to invest in complementary technologies that will greatly enhance the missions of the Air Force. Technologies that are essential are:

- On-focal-plane processing, especially for the hyperspectral sensors that can operate at cryogenic temperatures
- Optical processing for processing optical signals and for processing data by means of optical computing

- Data fusion technologies that take data from multiple phenomenology sensors and fuse the data in near real time
- Neural network and artificial intelligence (AI) technologies that can do automatic pattern recognition and knowledge extraction from fused data
- Advance packaging and electronics technologies for space that can dramatically reduce power consumption, weight, and volume

There are tradeoffs on where the processing, data fusion, and knowledge extraction have to be performed. With the advent of hyperspectral sensors and the growth in active sensors such as space-based radars and synthetic aperture radars (SARs), processing requirements onboard the spacecraft will increase dramatically to more than 10 Gflops per channel of the sensor. DoD investments to leverage commercial technologies and the complementary DoD unique technologies will be essential to keep the US superiority in space assets.

The Air Force must invest in real-time data fusion. (Data fusion is described in great detail in the report of the Sensors Panel.) In terms of payloads, defense satellites are likely to evolve toward clustered sensors, mixing both passive and active observations. Observation satellites will be members of clusters that use multispectral arrays of sensors: radar, lidar, hyperspectral, imaging, and possibly others. The fusion of this data from the satellite cluster will be essential to the efficient and timely operation of information gathering from space. Intelligent analysis of data will allow satellites to focus on interesting areas, and ignore regions of inactivity, in a fashion much like a human being looks at a scene. Advances in software, especially in artificial intelligence and neural networks, will be required for this effort. Preliminary demonstrations at Lincoln Lab have demonstrated automatic target recognition of ships using current neural network technology that is as effective at identifying ships as a human operator. Commercial applications of neural nets are developing, and are likely to increase dramatically in the next 10-20 years. The Air Force should invest to adapt commercial technologies in this field to enable such demanding applications as ATR in the future.

4.17 Applications of Spaceborne Weapons

The ability to deploy and use weapons from space is constrained by technology and policy issues. At this time national policy restraints are the most significant barrier to such implementation. It would be imprudent to ignore technological developments that could enable such a capability in the future.

The function of a spaceborne weapon is essentially the same as a weapon on any other platform, to deliver a damaging or lethal amount of energy to a target of the warfighter's choosing. In future conflicts, the ability to destroy or incapacitate a target in the most timely manner and with the least collateral damage possible will be at a premium. The potential global presence by a space-based system is attractive, but the long stand-off distances involved place significant demands on any weapons systems in space.

Space weapons could be targeted against terrestrial targets (Force Application) or against an opponent's space assets (Space Control). Destruction of a given target, depending on the situation, may not be desirable. Rather, it may be preferable to temporarily disable an opponent's capabilities for a specified period of time.

4.18 Design Considerations for Spaceborne Weapons

Design considerations for spaceborne weapons are driven by the requirement to place the right amount of energy at the right location to achieve the desired effect. Two technological approaches merit serious consideration for use as spaceborne weapons:

- Directed energy (RF and lasers)
- Kinetic kill

Of the two, directed energy is attractive in that it offers a range of responses. By adjusting the power density on the target, for example, the laser could modulate its impact from simply sending a message to an enemy (e.g., placing a low-power beam on an artillery crew to let them know that they are targeted) to destroying an offensive weapon such as an ICBM during its boost phase. Using directed energy to jam enemy communications or sensing systems constitutes a form of information warfare. (See the report of the Information Applications Panel for further discussions of the information warfare concept.)

4.18.1 The State of the Art in Spaceborne Weapons

Most of the technologies for a kinetic kill weapon (either a projectile dropped from orbit to the surface of the earth, or an interceptor targeted against another satellite) are available today; the greatest effort would be in integrating existing technologies into a functional system.

High-energy lasers exist in laboratories and have been successfully flown in military aircraft, but tend to be large. Much work has been devoted to high energy chemical lasers, such as hydrogen fluoride (HF) at 2.9 mm, or oxygen-iodine at 1.3 mm. Chemical lasers provide tremendous energy storage, and are capable of delivering tens to hundreds of megajoules (MJ) of energy per shot. The downside of the chemical laser is that it consumes its fuel, and thus has only a limited number of shots (although projection on the HF laser show that approximately 1600 MJ of stored energy is feasible, allowing hundreds of 10-MJ shots before recharging would be required). A second downside of the chemical laser is that, given the limited choice of viable chemical laser systems, an enemy is likely to know precisely what the wavelength of the laser will be, and would be able to take passive countermeasures to reduce the optical interaction on the target.

4.18.2 Technologies for Evolutionary Change in Spaceborne Weapons

Although kinetic kill vehicles are possible with current technologies, capabilities of such weapons would be significantly enhanced by MEMS technologies. The energy density of matter in LEO is on the order of 20 kilojoules per gram (kJ/g), so that a tiny maneuverable vehicle has large destructive potential. Miniaturizing sensors, guidance, and propulsion would enhance the utility of kinetic kill weapons by allowing them to be used with minimal collateral damage. Another set of technologies that would allow for a high degree of autonomy for kinetic-kill vehicles would bring the concept of a smart interceptor closer to reality. Kinetic-kill vehicles could be effective whether directed at ground- or space-based targets.

For directed-energy application, evolutionary advances in electrically-powered solid state lasers (semiconductor diode or optically pumped dielectric schemes) will lead to new wavelengths and power levels. All-solid-state lasers with 10 MJ per shot will be possible in the next decade

with volumes of less than 1 m^3. The technology for the high power laser, either chemical or solid state, should be available in the next decade. The Air Force should continue research to achieve this level of performance.

Wavefront control and correction of the laser beam are required to deliver focused energy (< 30 cm spot size) on target after propagation through a turbulent atmosphere. This can be achieved today using phase conjugation based on four-wave mixing in nonlinear optical media using the output from a single-mode laser, or by adaptive optics ("rubber mirrors"). In the future it may be possible to create an array of semiconductor lasers that could be phase-controlled for targeting. Research into phase locking of individual diode lasers is an attractive research topic for industry and academia. Further basic research will be required to determine whether phase control of large arrays of individual lasers is feasible.

Large mirror optics with diameters of approximately 20 meters will be needed to focus a laser beam to the desired spot size. This technology must be developed. NASA is working on innovative ideas such as inflatable mirrors for civil space applications. Advances and developments in this area are critical to the space-based laser weapon.

Finally, the laser and mirror must be precisely aligned and pointed for target destruction. To use a desirable f/10 optic, the laser should be approximately 100 meters from the mirror. Either a large space frame will be needed, or precision stationkeeping of the independent laser and mirror will have to be established. Advances in constellation control and precision stationkeeping will be required.

Space control activities in the coming decades will need a spectrum of weapon systems. Microwave weapons have some advantages that the Directed Energy Panel report has covered in much more detail. With commercial space technology proliferating, potential adversaries are likely to have the same space sensing, communications, and navigation capabilities as the US currently has. In this regard, information warfare technologies will be playing a critical role in the next century and microwave weapons including electronic warfare (EW) and high power microwaves can play a key role in this area.

The Air Force should invest in developing space-based information warfare technologies that have the potential for disabling and or permanently damaging the adversary's spacecraft. Some of these technologies include disposal jammers, jamming and high power radiating satellites. Technologies that will make these feasible include high efficiency RF power converters, lightweight antennas, long-life, lightweight batteries and high-efficiency power generation systems. There are a variety of tradeoffs in being able to perform these activities (e.g., space-based versus airborne platforms) and those constraints will dictate the development of these technologies.

4.18.3 Technologies for Revolutionary Change in Spaceborne Weapons

The toughest technological challenge for the high-energy space-based laser is power generation and energy storage. Assuming overall 50% electrical energy conversion efficiency, a 10 MJ laser would require 20 MJ of stored energy per shot. One shot of this weapon every 20 seconds would require 1 MW of power. This power could be stored on board in supercapacitors or high-energy-density flywheels. However, replenishment of this power in a timely manner would be enabled by the development of technologies for high power generation in space. As

discussed in the spacecraft bus chapter, technologies in which the Air Force must invest include nuclear power, electrodynamic tethers, and laser power beaming.

A companion issue to power generation is thermal management. (Chemical lasers such as the oxygen-iodine laser can directly discharge their reactants and thus have a small effective thermal load, but they also have a limited fuel supply and are extremely expensive per shot.) The 0.5 MW of waste power generated by the operation of this hypothetical laser would need to be radiated away in order for the system to operate. Handling such large heat loadings is beyond the capability of current practice; technologies that would enable thermal management of high-power systems are as critical as power generation in those systems.

4.19 Recommendations for Investments in Spacecraft Payload Technologies

The Air Force should follow a carefully targeted plan of investments in spacecraft payload technologies, investing for both revolutionary and evolutionary improvements in spacecraft payload capabilities.

4.19.1 Revolutionary Spacecraft Payload Technologies in Which the Air Force Must Invest

Several key spacecraft payload technologies offer the possibility of a substantial increase in the exploitation of space by the Air Force, the potential impact of which is so great that the Air Force must invest now. These technologies are:

- Technologies for high power generation (greater than 100 kiloWatts) such as nuclear, laser power beaming, and electrodynamic tethers
- Technologies for clusters of cooperating satellites (e.g., high-precision stationkeeping, autonomous satellite operations, and signal processing for sparse apertures)

4.19.2 Evolutionary Spacecraft Payload Technologies in Which the Air Force Should Invest

The Air Force should invest for evolutionary improvements in performance or reduced life-cycle costs to its systems. The technologies that offer such benefits in the area of spacecraft payloads are:

- Sensor technologies:
  - Large, sensitive focal plane arrays and associated readout and cooler technologies for hyper - and ultraspectral sensing of small low-contrast targets and long wavelength detection against the cold background of space
  - Active sensor technologies (e.g., large lightweight antennas, high-efficiency radio frequency (RF) sources for synthetic aperture radar (SAR) and moving target indicator (MTI) radar, and high-energy lasers for lidar)
  - Microelectromechanical systems (MEMS), including on-chip optics

- Communications technologies
  - Very high rate, long-distance optical communications
  - Multi-beam adaptive nulling antennas for anti-jam communications
- Data fusion technologies, including automatic target recognition
- Space-based weapons technologies
  - Laser weapons technologies (e.g., large lightweight optics)
  - Technologies for smart interceptors (e.g., autonomous guidance, MEMS)
  - RF weapons technologies (e.g., lightweight energy storage) for electromagnetic pulse (EMP) and jamming

4.19.3 Commercially Led Spacecraft Payload Technologies

Another set of technologies that will allow for evolutionary change spacecraft payloads will be driven by the commercial sector. These technologies merit minimal investment by the Air Force, yet the Air Force should invest as is necessary to adapt these technologies to its needs. These technologies are:

- High-efficiency energy conversion and storage
- High-data-rate RF communications
- Information storage, retrieval, and processing technologies and protocols
- Image processing, coding, compression, and very large scale integration (VLSI) architectures
- Neural networks and artificial intelligence

5.0 Crosscutting Technologies

5.1 Introduction

The government has made significant investments in space systems and technologies that have enhanced communications, weather prediction, navigation, and remote sensing. Much of today's commercial space industry is based on these past government investments. Commercial industry will invest in those technologies and systems for which there is an acceptable risk and return on investment. Industry is not likely to make large, high-risk investments of the type the government has made in establishing the viability of various fundamentally new space applications.

Today's commercial use of space is market driven. Services are provided by space systems that are either unique, more cost-effective, and/or better than what can be provided by other means. Industry is taking advantage of rapid advances in electronics, communications, and information technologies to increase the aperture of space activities that are commercially viable and this trend will continue. Reductions in costs associated with launch, satellite and payload design and production, and space systems operations will also continue to expand the horizons of what is commercially viable in future space systems.

The Air Force of the future must control the high ground of space with systems that are affordable. Affordability will require investments to adapt rapidly advancing technologies and processes from commercial efforts to the needs of the Air Force. This is especially the case in spacecraft manufacturing and operations, where technical advances and commercial practices are substantially reducing manufacturing cycle times, development costs, and operations manpower and costs.

Affordability of function will require a radical shift in the way the Air Force does business in space. Part of this shift will be cheaper, lighter spacecraft launched on cheaper boosters. Another important aspect will be the advent of distributed satellite systems.

In an era of a maturing commercial space industry, the Air Force's hierarchy of preference in acquiring space capabilities should be to buy commercial services where possible and where no compelling military advantage is available at reasonable expense from military augmentation or dedicated systems. Where commercial services are not adequate or appropriate, the Air Force should seek opportunities to augment commercial systems. Where augmentation is not appropriate, the Air Force should, where possible, purchase derivatives of commercial systems using commercial-like procurement practices. Where derivative systems are inappropriate, the Air Force should employ, where possible, commercial commodity bus and payload subsystems and components in military systems. Only as the last resort should the Air Force have to procure specialized satellites, subsystems, and components.

5.2 Commercially Led Technologies for Spacecraft Manufacturing

Spacecraft manufacturing has traditionally been a low-volume, high-cost, high-technology, craft production enterprise. Today's competitive communication satellite marketplace is forcing a paradigm shift leading to substantial reductions in manufacturing cycle time and cost. Standard manufacturing process improvements are being introduced, including statistical process control, lean and agile manufacturing techniques, and use of multi-skilled teams.

Several relevant technologies are emerging that can be adapted to Air Force spacecraft program needs. These include:

- Built-in self test (BIST)
- Multifunctional structures (MFS)
- Accessible stored knowledge (ASK)

A great deal of the manufacturing cycle time and cost are taken with testing because process control alone is insufficient to ensure quality. The BIST concept is to embed hardware and software into electronics to detect, isolate, and either report or correct faults. Use of self-testing electronic systems for fault-tolerant satellites will enable higher quality testing at lower cost for manufacturing and integration of spacecraft. This test hardware and software can be used for health monitoring during the operations phase. Hence, BIST will result in reduced design cycle time, improved system quality, and enhanced system operation.

The rapid advances in large-scale integrated electronics packaging, lightweight composite structures, and high-conductivity materials are enabling the development of an important new manufacturing and integration technology called multifunctional structures. The overall MFS concept is to embed electronics assemblies (e.g., multi-chip modules or MCMs), miniature sensors, and actuators into load carrying structures along with associated embedded cabling for power and data transmission. This level of integration effectively eliminates traditional boards, boxes, large connectors, bulky cables, thermal baseplates, etc., thereby yielding major weight, volume, and cost savings. Studies show that elimination of cables and electronic enclosures, along with full utilization of lightweight composite structures, could yield up to a 70% weight saving and 50% increase in available volume over traditional structural and electronics packaging techniques. These integrated modular structures could be designed to be highly reliable, reproducible, and repairable, and amenable to low cost manufacturing processes. Each major improvement in miniaturization of components, sensors, and devices becomes a candidate for integration into MFS. For instance, thin film technology, embedded antennas, structural vibration isolation devices, and other smart materials applications are natural inclusions into this global concept.

The technology enabling digital recording, storage, manipulation, and transmission of images (accessible stored knowledge) is advancing at an astounding rate. For example, design engineers, manufacturing engineers, and management have all been using computers and work stations to simplify their tasks. With advanced ASK technology, the worker on the shop floor can now get help with an ever-increasing complexity of tasks. Traditionally, manufacturing process plans have come to the shop floor in the form of sketches, diagrams, and written work instructions, all drafted by process engineers. Now, the technology is in place to provide the shop floor technician clear, concise instructions for the work to be performed in an easily understood way, i.e., in the form of computer-generated imagery. The time required for understanding a work plan then goes from hours to minutes, and the quality of understanding is substantially better. Potential problem areas can be graphically illustrated for knowledge retention. The use of animation, and eventually virtual reality, will accelerate training and improve quality. Air Force funding should be focused on adapting commercially available technologies to Air Force needs in terms of standards, techniques, and methods such as these.

5.3 Commercially Led Technologies for Spacecraft Operations

Spacecraft control and operations have traditionally been unique, highly mission-dependent endeavors tied to a diverse suite of hardware and software developed independently with little or no commonality across platforms. The same competitive forces that are driving changes in satellite manufacturing are also having an impact on how satellites are operated as part of the effort at overall life cycle cost reductions. Increased use of technology and migration to standards and open architectures will serve as catalysts for operational changes.

Driving technologies likely to affect future spacecraft operations will include advances in:

- Digital processing
- Software
- Computing power
- Communications

These technologies will enhance all aspects of the overall spacecraft system, including both space and ground assets, the links between them, and the effectiveness of the people who operate and maintain them. Advances in digital processing being seen today will provide for data compression techniques that improve both bandwidth and data storage capacities, beam shaping algorithms for improved transmission efficiency, and fault-tolerant architectures with self-correcting properties to assure continued operation even under the most adverse of conditions.

The explosion of information systems in recent years has pushed both computing power and software to new levels of speed, complexity, and overall performance. Automated code generation, advanced testing and verification techniques, graphical user interfaces, modular software development, and software reuse are current capabilities that are being applied in commercial software development and will enhance space operations capabilities as they are introduced to that domain. Possibly more significant are the improvements in computing power that provide for increased data storage density and increased processing speed without increased power demands and that serve as the enabling technology for the migration to distributed client/server architectures for nearly any application.

Software represents an increasingly large portion of the development, operations, and maintenance costs associated with space systems. As a crosscutting technology, advances in this domain, which are being driven by the commercial software market, will have significant impacts across the launch vehicle, spacecraft, and ground segments of the system. Object-oriented software development methodologies provide a mechanism for building code that is inherently modular and which fosters reuse. Integration of commercial off-the-shelf (COTS) software further lowers development costs with a penalty, however, of the increased configuration management problems as commercial software is upgraded or discontinued. Advances in open software architectures and standardization such as the common object request broker architecture (CORBA) remove many of the barriers to COTS integration and reuse. Advances in expert systems and improved software algorithms enable more intelligent processes for planning and scheduling and decision aids for anomaly resolution. Graphical user interfaces will migrate to intuitive object and event based interaction that facilitate more robust visualization and higher abstractions for user interaction with the system. Many of these advances, particularly when

coupled with a capability for automated code generation from high level designs and integrated software development environments, allow for rapid functionality enhancement, improved code quality, and the development of the more complex software required to support such tasks as autonomous satellite operations, constellation payload and resource management, and multiple mission management.

Communications technology is another arena where advances are rapid and applicability to the space environment is natural. As bandwidth demands increase, technical solutions include media changes to support the higher frequencies required. Current efforts in fiber networks and laser communications (both in fiber and line-of-sight) are examples of areas where spacecraft and ground operations will benefit from commercial advances. Data compression techniques provide virtual bandwidth expansion and help minimize uplink requirements. Protocol advances such as the development of demand-assigned multiple access (DAMA) further enhance the capability of communications networks supporting the space mission, providing improvements in efficiency and making this resource more ubiquitous and robust. Increases in integration and the improved functionality available in smaller components are trends that provide for increased space-based capability and the move to smaller, autonomous payloads.

The impact of technology on spacecraft operations is potentially dramatic, with a shift from flying spacecraft to autonomous spacecraft operations clearly on the horizon. Today, non-standard telemetry, tracking, and command and control processes lead to costly, complex, and unique requirements for both satellites and the supporting ground infrastructure. Limited onboard data storage and processing capability force mission-dependent architecture differences and require system specific training of operational personnel, as well as unique test equipment and procedures. The movement to almost all digital processing will alleviate this as existing systems are replaced and extended. This technology, which dominates tracking, telemetry, command and communications subsystems, has reduced ground station facility footprints and reduced greatly the need for the tuning and matching of equipment. Both of these factors will allow for the reduction in both facilities costs and maintenance personnel costs. The incorporation of very extensive and responsive built-in test equipment along with the inherent reduction in failure rates for digital circuitry will continue to reduce the life-cycle cost of these systems.

As with digital processing, the emphasis today in exploiting client/server technology is reducing in life-cycle cost and avoiding obsolescence for existing spacecraft systems. There will clearly be few if any new starts sparked by technology for any other reasons. An additional aspect of the distributed computing evolution is its applicability in supporting system consolidations. Consolidation applies to both the direct command and control of space assets and to the decision support systems associated with the utilization of remote sensing system products. Client/server distributed computational systems, communicating over local and wide area networks, will exploit the de facto industry standards and COTS products to maximize future resistance to obsolescence. Improved data base synchronization techniques, operating in near real time while still ensuring total data integrity, are opening up consolidation opportunities for geographically diverse systems and the opportunity to do remote data systems administration from centers of excellence, including contractor facilities. This clearly should reduce the maintenance staffing of those consolidated data systems. The disadvantage in the near term is that the level of expertise required to maintain these systems must rise at the same time, thereby putting pressure on the critical skill pools available.

Overall mission operations will benefit from technology advances by improvements to mobility, reliability, availability, and security. Lower cost and smaller ground stations provide the potential for increasing the number fielded with the benefit of more timely data dissemination and increased survivability. Vulnerability of the spacecraft segment is reduced by mission profiles relying on autonomous satellite operations with payloads containing integrated C^3I capability. Multi-mission capability and cooperative constellations additionally enhance the flexibility of limited assets.

Spacecraft operations concepts will evolve to adapt to this technology and require a corresponding update to the skills of the personnel operating these systems while facilitating decreases in staffing needs per mission. Intuitive and goal-based interfaces will decrease training requirements and provide for common training across multiple missions; however, the increased operator capability and task complexity imply an increase in the overall system (as opposed to subsystem or task) knowledge required. Use of decision support functionality and built-in test capability will be a key skill.

The fundamental benefit of technology on spacecraft operations is to provide increased functionality and/or lower life-cycle costs. Evolutionary changes to systems, enabled by use of COTS, reuse, and modular designs, not only extend system life time, but lower maintenance costs and shorten cycle times for technology or platform upgrades. Future systems must exploit this by mandating designs that not only provide for incremental changes, but encourage the process as a fundamental way of achieving operational requirements.

5.4 Technology Insertions in Spacecraft Manufacturing and Operations

Specific impacts of technology on each segment will tend to migrate from ground based insertions towards satellite changes eventually providing a degree of autonomy to spacecraft operations that will include resource management, fault detection/correction, and mission planning, scheduling, and execution, all onboard the spacecraft using expert systems and fuzzy logic. Increased processing speed and data storage will enable onboard functionality for even the traditional ground station functions such as command generation, anomaly detection, and data extraction. Open architectures for spacecraft computing and maximization of software reuse will provide for modular designs that lower the cost of upgrades and technology insertions, allowing multiple payload types to fly on a common bus. Communications improvements, coupled with increased on board processing, will meet the telemetry and mission data bandwidth needs of future systems. The establishment of high-bandwidth satellite-to-satellite links using laser or other technology could quickly make cooperative constellations of spacecraft the norm, particularly if coupled with onboard GPS-based positioning and attitude determination. Such constellations would further enhance system reliability, adaptability, and robustness.

Not to be ignored are the near term impacts of technology on the ground station segment. These changes will be introduced more rapidly and in an evolutionary manner due to the better access available. The migration to client/server computing architectures is already having an impact by decreasing the required ground station footprint, enhancing portability, and providing the potential of multi-mission capability. The fault tolerant architectures being developed (along with improved reliability of COTS data processing equipment) will provide for decreasing

maintenance requirements that will help reduce life-cycle costs in addition to their primary goal of improved robustness and survivability. Advances in ground station software have allowed for the introduction of the graphical user interface (GUI) as the primary interaction with the system. Further enhancement to this paradigm will improve the controller's interaction and understanding of the spacecraft and system status with the development of goal-oriented, event-driven commanding and standardized interactive displays. Modular and standards-based designs provide for iterative upgrades to ground station functionality based on advances in technology, functionality, COTS products, or changes in operations concepts. Coupled with automated code generation, new functionality or anomaly resolution will be inserted more rapidly and with greater confidence into operational systems. A key aspect to facilitating continued software technology insertions is that all future software should be designed to be portable to space, independent of its original processing location.

For the ground segment, a possible technology insertion path is as follows:

- Rethink the basic concept of operations for each mission type with the goal of automating routine operations and minimizing routine uplink
- Design any new ground segment software to be portable to space
- Standardize a high-level event definition language to reduce commanding and uplink
- Standardize data and rule representations for rule-based expert systems to allow system reuse

Similarly, for the space segment, a possible approach is:

- As a general approach, utilize the subsumption architecture as a paradigm for developing spacecraft autonomy
- Automate health and status monitoring
- Introduce autonomous spacecraft safing
- Utilize the Global Positioning System (GPS) for autonomous positioning, timing, and attitude determination with automatic reinitialization
- Utilize one-way status monitoring system (vital signs)
- Move command generation on board the satellite to reduce uplink and improve efficiency of spacecraft resource utilization
- Develop open architectures for spacecraft computing and software reuse along with standards for reprogrammable memory, command verification, and telemetry buffering
- Implement onboard anomaly detection and redundant system switch-over
- Design systems to send diagnostic information down as part of vital sign message
- Design systems so that if problem is serious, an emergency signal is sent, using Iridium-type approaches if necessary to page a cognizant operator

5.5 Recommendations for Crosscutting Technology Investments

Essentially all of the technologies that will allow for evolutionary change in Air Force space operations will be driven by the commercial sector. These technologies merit minimal investment by the Air Force, yet the Air Force should do what is necessary to adapt these technologies to its needs. These technologies are:

- Technologies for Spacecraft Manufacturing
  - Built-in self test (BIST)
  - Multifunctional structures (MFS)
  - Accessible stored knowledge (ASK)
- Technologies for spacecraft operations

6.0 Conclusions and Recommendations

6.1 The Value of Space to the Air Force

The foundation of the New World Vistas study is a vision of the 21st century and how the Air Force will do business in the future. One current trend that will almost certainly continue is the demand that the Air Force do more with less; hence the directive to the Space Technology Panel to identify technologies that fundamentally increase US capabilities in space and significantly lower the costs of operating there. High-risk/high-payoff technologies have traditionally been funded by DoD, where each service keenly recognizes the necessity of keeping the technological edge on the battlefield.

The Air Force must maximize its return on its investment in technology. Although today space may be the Air Force's "best kept secret," space assets proved their worth during Operation Desert Storm and the Air Force's use of space will only increase in the future. Space provides unparalleled access to regions of potential conflict. Space assets are timely, with low-earth-orbiting platforms spanning the globe in 90 minutes and geostationary satellites offering continuous coverage of large areas of the earth. Such an expanding area of operations offers a large payback for technologies that can improve affordability and capability.

6.2 Visions of Spacecraft Technology

The technology of placing a payload outside the earth's atmosphere and having that payload perform a useful task has steadily evolved since the early days of rocketry in the 1940's. This evolutionary process will continue. The Air Force should invest in technologies that steadily improve future generations of space systems, but the highest payoff will be found in areas that fundamentally change the way the Air Force does business in space, whether by enabling new capabilities or significantly reducing costs.

6.2.1 The Evolution of Space Technology in Coming Decades

Over the near term, the driver for space systems will be reducing the cost to perform a particular function in space, which means reducing the life-cycle costs of a given space system. Life-cycle costs consist of three elements:

- The cost to develop and produce the spacecraft
- The cost to launch the spacecraft
- The cost to operate the spacecraft

Historically, the cost to build and launch a spacecraft has scaled, to lowest order, with its mass. This empirical truth is a function of the current paradigm for space. Air Force space payloads share several common characteristics. They are typically:

- Large (10,000 lb)
- Expensive ($40,000/lb to develop, independent of launch costs)
- Essentially custom built
- Multi-mission or multi-function

- Independent of other spacecraft
- Controlled in detail from the ground

The current paradigm presents several disadvantages. Because space assets are so expensive, failure of a system is prohibitably costly. Thus, systems are conservatively designed, based on known and trusted technologies, and rigorously tested (which drives up costs). Systems are called on to perform many tasks rather than being optimized for one role. Although a serious antisatellite (ASAT) threat has not materialized to date, the cost, both in dollars and in functionality, of losing even one satellite to hostile action would be extremely high. The infrastructure, both in equipment and personnel, to operate these platforms is significant. Over the near term, the economic driver for space systems is likely to be dollars/pound to orbit, which argues for technologies that:

- Reduce the cost of launching a given mass
- Reduce the mass of a given payload capability

The most basic problem of space operations, namely, placing a payload in orbit, has historically been solved with chemical rockets. No competing technologies are sufficiently mature to break this monopoly in the coming decade. Therefore, the coming decades will likely see evolutionary changes in launch vehicle technologies that will, over time, yield significant cost savings. There are two paths along which chemical rockets can evolve:

- Expendable launch vehicles
- Reusable launch vehicles

The costs of expendable launchers could be reduced by increasing the payload mass fraction. The ideal chemical rocket would consist of nothing but payload and fuel; the mass of the structure devoted to storing the fuel, moving it, and combusting it in a controlled fashion (the tanks, engines, etc.) is vital to the function of the rocket but is dead weight from the standpoint of payload to orbit. If the components of the launch vehicle could be made of very lightweight materials, then the portion of the mass lifted into orbit that is useful payload would increase and the cost per pound would decrease.

Other economies could be realized by making expendable vehicles simpler to manufacturer and to operate. Exotic materials that are difficult (and hence expensive) to work with and result in marginal weight savings increase the cost of placing a given payload in orbit. Reducing the number of manufacturing steps is another avenue for reducing costs. Finally, reducing the costs of operating the launch vehicle and the number of personnel required to launch it is a means of cost reduction.

Overall, the foreseeable cost reductions of advanced expendable launcher technologies are on the order of factors of 30-50%, which is significant only in the short term.

The same technologies that could be applied to increasing payload mass fraction and simplifying manufacturing and operation of expendable launch vehicles could also be applied to reusable launch vehicles, which would offer the additional economic advantage of spreading the cost of the vehicle itself over many launches. The key to the success of a such a launch vehicle would be making as much of it as possible truly reusable, more like an aircraft that

requires only refueling and some routine maintenance between flights than a rocket or even the Space Shuttle, which requires significant refurbishment between flights. Materials technologies that would allow engines to operate at high-temperatures without damage, or that would enable the use of non-ablative heat shields upon reentry, would allow the reusable launch vehicle concept to be economically viable. The reusable launch vehicle offers possible cost saving of an order of magnitude or more over the present state of the art, and thus is a more viable concept for the long term.

Reducing the cost of a particular payload capability centers on two approaches:

- Building payload components from lightweight materials
- Reducing the size of payload components

Some of the same materials technologies that could be used to decrease the mass of a launch vehicle could be used to reduce the mass of a payload structure as well. Furthermore, any spacecraft, regardless of its mission, must perform certain basic functions. It must generate or gather power, store energy for later use, convert prime power into electrical power to run its other systems, communicate with the ground, and manage its attitude and configuration. A satellite or other payload would benefit from technologies that allow power generation and conditioning, and energy storage in lower-mass packages, or from lightweight deployable antennas or solar panels. Some technologies, such as optical computing, may allow for both increased performance and reduced mass for data buses as copper wires are replaced with glass fibers.

Miniaturization of components offers multiple benefits; smaller components are not only less massive in their own right, but typically require less power, shorter interconnects, etc., reducing demands on the supporting systems of the spacecraft. Micro-machining techniques, the descendants of integrated circuit technologies, offer the prospect of orders of magnitude decreases in the size of some components.

Decreased payload mass and decreased cost/pound are complementary approaches to reducing the overall cost of performing the Air Force mission in space.

6.2.2 A New Paradigm for the Air Force in Space

The Air Force should try to develop not only those technologies that incrementally improve capabilities in space, but those that enable a radical change in the present paradigm for activities in space. One can reasonably project technologies that, over the next few decades, would allow the Air Force to abandon the current mode of operation in favor of another where its space payloads would be:

- Small (less than 1000 lb)
- Inexpensive
- Mass-produced
- Optimized for a single function
- Networked with other space assets
- Highly autonomous

In addition, one can project technologies that would make much higher levels of power available to spaceborne assets. This would enable many capabilities that at present do not exist, whether in the areas of communications, active sensing, or force application. Under this model, each space asset would operate as part of a larger system in space. This approach offers several advantages. Systems of satellites would be inherently more robust than a single satellite performing the same function; if any single satellite were to fail or be destroyed, the system as a whole would continue to operate. The system itself could be reconstituted or upgraded by launching new payloads. Autonomous systems by their nature would require a smaller infrastructure to operate. The goal of greater capabilities at lower cost would become attainable.

6.3 An Investment Strategy for Technologies

The reduction of resources available to the DoD in the post-Cold War era means that DoD investment in space technologies and space systems must be firmly rooted in the goal of affordable systems. To this end, the DoD must plan its technology investment with a clear view of technological advances in the commercial world. It is undesirable and unnecessary for the DoD to develop every technology for its space systems on its own. There are many technologies that the commercial sector will develop that the military can adapt for its use with minimal investment. On the other hand, there will always be unique requirements for military systems that necessitate the use of technologies that have no commercial application, that push the performance limits of dual-use technologies, or whose timescale and risk are not attractive to the commercial sector. The DoD should carefully target its investments in technology to achieve the highest possible return. Technologies that are candidates for DoD investments fall into one of three possible categories:

- Revolutionary technologies in which the DoD must invest vigorously, because they are critical to the military mission and have little or no application in the commercial sector; without DoD investment, these technologies will not advance. These technologies will enable a *substantial increase in the exploitation of space* by the DoD. They will enable functions that are currently unaffordable or technically impossible.

- Evolutionary technologies in which the DoD should invest, because they are similarly critical to the military mission and have little or no commercial application. These technologies will enable gradual improvements that over time can significantly improve the performance or reduce the life-cycle costs of military systems.

- Technologies in which little DoD investment is required, because they will be led by the commercial sector. In these areas, the DoD should carefully monitor the progress that industry is making and invest only to the level necessary to adapt commercial technologies to the military mission.

The DoD should not underestimate the benefits of a healthy synergism between military and commercial research and development.

6.3.1 Revolutionary Technologies in Which the Air Force Must Invest

Several key technologies offer the possibility of a substantial increase in the exploitation of space by the Air Force, the potential impact of which is so great that the Air Force must invest now. The first three of these technologies will enable much larger payload fractions to be lifted to orbit by factors of four or more and combined with affordable operations will enable much cheaper access to orbit. Therefore they have the potential to revolutionize the launch equation and remove the significant barrier that high launch costs impose. These technologies are:

- High-energy-density chemical propellants to enable spacelift with high payload mass fractions—specific impulses of 1000 seconds or greater (in high-thrust) systems should be the goal of this effort
- Lightweight integrated structures combining reusable cryogenic storage, thermal protection, and self diagnostics to enable a *responsive* reusable launch capability
- High-temperature materials for engines and rugged thermal protection systems

The next two technologies will enable space-based weapons such as high power lasers, space-based radars with wide search areas and satellites that can maneuver almost at will. They have the potential to substantially remove orbital dynamics as a barrier to where satellites can go. These technologies are:

- High performance maneuvering technologies such as electric propulsion (with thrusts greater than tens of Newtons at specific impulses of thousands of seconds at near 100% efficiency the goal for electric propulsion) and tethers for momentum exchange
- Technologies for high power generation (greater than 100 kiloWatts) such as nuclear power, laser power beaming, and electrodynamic tethers

The final set of technologies will enable a new vision for space applications where functionality is spread over many satellites rather than only in a single satellite. They have the potential to enable new applications from space (such as Global Awareness) at affordable cost. These technologies are:

- Technologies for clusters of cooperating satellites (e.g., high-precision stationkeeping, autonomous satellite operations, and signal processing for sparse apertures)

6.3.2 Evolutionary Technologies in Which the Air Force Should Invest

The Air Force should invest for evolutionary improvements in performance or reduced life-cycle costs to its systems. The technologies that offer such benefits are:

- Launch vehicle technologies
  - Engines, upper stages, and solar thermal propulsion
  - Vehicle structures (e.g., aluminum-lithium or advanced composite tankage, as well as multifunctional structures)

- Satellite bus technologies
  - Structure technologies (e.g., lightweight structures, active vibration suppression, precision deployable structures, and software-controlled multifunctional surfaces)
  - Innovative energy storage technologies (e.g., the electromagnetic flywheel battery)
  - Attitude control technologies, including attitude sensors and attitude control system (ACS) algorithms
  - Radiation hardening technologies for spacecraft electronics
  - Low-observable technologies
  - Microelectromechanical systems (MEMS) technologies
- Sensor technologies
  - Large, sensitive focal plane arrays and associated readout and cooler technologies for hyper- and ultraspectral sensing of small low-contrast targets and long-wavelength detection against the cold background of space
  - Active sensor technologies (e.g., large lightweight antennas, high-efficiency radiofrequency (RF) sources for synthetic aperture radar (SAR) and moving target indicator (MTI) radar, and high-energy lasers for lidar)
  - MEMS (including on-chip optics)
- Communications technologies
  - Very high-rate, long-distance optical communications
  - Multi-beam adaptive nulling antennas
- Data fusion technologies, including automatic target recognition
- Space-based weapons technologies
  - Laser weapons technologies (e.g., large lightweight optics)
  - Technologies for smart interceptors (e.g., autonomous guidance, MEMS)
  - RF weapons technologies (e.g., lightweight energy storage) for electromagneticpulse (EMP) and jamming

6.3.3 Commercially Led Technologies

Another set of technologies that will allow for evolutionary change in Air Force space operations will be driven by the commercial sector. These technologies merit minimal investment by the Air Force, yet the Air Force should invest as necessary to adapt these technologies to its needs. These technologies are:

- Small launch vehicles

- High-efficiency energy conversion and storage
- High-data-rate RF communications
- Technologies for debris reduction
- Information storage, retrieval, and processing technologies and protocols
- Image processing, coding, compression, and very large scale integration (VLSI) architectures
- Neural networks and artificial intelligence
- Technologies for spacecraft manufacturing
- Technologies for vehicle and spacecraft operations

6.3.4 Recommendations for Management Improvements

Space technology development occurs currently under NASA, DoD, NRO, DoE, and industry auspices. Execution of the resulting programs is only loosely coordinated through teaming, informal communication between investigators, professional society fora, and ad hoc topical organizations. Planning of the technology investment and programs by the various agencies is largely independent and uncoordinated. To create an efficient, coherent national space technology strategy, the Air Force should take the lead in establishing collaborative planning, advocating appropriate changes to US Space Policy, and encouraging coordinated execution of space technology development among all these organizations.

The chance to exploit commercial leads in some space technologies presents the opportunity for reduced government technology investment, reduced cycle time, and lower cost space systems, but, the ability to reap those benefits requires the discipline to accept the constraints of commercial capability in acquisition and in technology investment.

The recommended revolutionary and evolutionary technologies will provide the greatest benefit to the Air Force in the future and will not be developed by the commercial and civil communities. The least expensive route to meet the future needs in space is a sustained government investment and continuity of effort.

In conclusion, the Space Technology Panel has determined:

- The international exploitation of space services will grow
- The Air Force will be able to take advantage of complementary commercial investment
- There are revolutionary technologies that will enable a new vision for the Air Force in space
- To effectively support the warfighter from space, active and sustained investment in these revolutionary technologies is essential

Appendix A

Panel Charter

The Space Technology Panel's charter as derived by SECAF letter, 29 Nov 94, and discussions with Dr. Gene McCall, Chairman of the Scientific Advisory Board, was to:

- Identify new technologies for space applications in a 10-30 year timeframe which will offer:
  - Fundamental improvements in Air Force capabilities
  - Significantly lower costs for existing capabilities
- Consider the impact of commercial or dual use technologies for space for the future and identify the technology path for incorporation into Air Force systems
- Seek out technologies that may lead to new paradigms in space applications

Space Technology Panel Process

The Space Technology Panel conducted a series of information gathering sessions, listed in Appendix C, beginning in March 1995 and concluding in July 1995. The panel solicited information from a variety of government, industry and academic sources. To focus the information received, the panel asked the following questions:

- What is the current state of the art in space technology?
- How will space technology evolve over the next 10-30 years?
- What impact will technology have on the affordability, performance and capability of Air Force systems?
- What technologies will the commercial world develop?
- What technologies should the Air Force invest in and which should they buy?
- What will be the costs (development, adaptation and incorporation) of these technologies and how well can these be predicted?
- What is a technology roadmap from the current technologies to the future?
- If current limitations on launch, power, bandwidth, etc. were removed, what space applications would be possible and what technologies would enable them?

At the same time the Space Technology Panel conducted its investigations of technologies, the Space Applications Panel was gathering information, generating ideas, and identifying issues dealing with requirements, missions, and concepts. These two panels interacted routinely to ensure consistency and completeness in the panels' conclusions and recommendations. The Space Application Panel provided insight into market or threat driven needs and areas where current technology investment was insufficient to meet military requirements (requirements

pull). The Space Technology Panel provided the Space Applications Panel input on emerging technologies that could offer significant new applications or improvements (technology push), such as rapid advances being made in computers, micromechanical devices, sensors, information technology, materials, and multi-functional structures.

In addition to briefings from various organizations and interaction with the other New World Vistas panels, the Space Technology Panel reviewed recent studies and reports (listed in Appendix G), including *Spacecast 2020*, *Seven Strategies for Space*, the *Space Critical Technologies Study*, the *Space Launch Ad Hoc Study*, and the *Space Launch Modernization Study* (Moorman Study). The panel also requested white papers from numerous organizations; these are listed in Appendix F.

Appendix B

Panel Members and Affiliations

SAB Members

Prof. Daniel E. Hastings, Chairman
Professor and Associate Department Head,
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

Dr. William F. Ballhaus, Jr.
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Lt Col David G. Hincy
Executive Officer
USAF Scientific Advisory Board

Appendix C

Panel Meeting Locations and Topics

16 March Falcon AFB, CO

- New World Vistas Overview, Roles & Missions of the US Space Force, Future Space Technologies - AFSPC View, Space & Missile S&T Overview

17 March Falcon AFB, CO

- Launch Vehicle Technology Perspective, Spacecraft Technologies - In Support of a New Reality, TENCAP

13 April Phillips Laboratory, Kirtland AFB, NM

- Introduction and Welcome, Overview, ALEXIS FORTE, Multi-Spectral Thermal Images, Experimental Space System, Fluorescent Refrigerator ,SAWAFE, Advanced Propulsion Concepts, Advanced Materials Development, Nuclear Power/Propulsion/Bimodal/Space Power, Space Communications Space Sensors

14 April Phillips Laboratory Kirtland AFB, NM

- Space Experiments, Reusable Launch Vehicles/LV Technologies, Space Electronics, Satellite Control, Space Structures Technology Integration, Space Technology Programs

10 May Lincoln Laboratory, MA

- Innovative Space Technologies and Applications, Spacecast 2020, NASA Perspectives, International Activities, Space Laser Communications, Space Sensor Technology (Electrooptical), DoD Satellite Communication, Air Force Basic Research

11 May Lincoln Laboratory, MA

- BMDO Technologies, Geophysics Technologies, Overview, Space Particle Modification for Defense/Offense, Precise Tracking and Targeting Satellite Networks, Weather Modification

12 May Lincoln Laboratory, MA

- Multispectral Hi-Resolution Sensors, Haystack Observatory, Launch Vehicles, Space Critical Technologies, Innovative Concepts

21 June Jet Propulsion Laboratory Pasadena, CA

- Overview, Sensor and Information Processing Technology, Second Generation Microspacecraft Study, Hyperspectral Imaging Systems, Synthetic Aperture Radar (SAR), JPL Tour

Aerospace Corporation El Segundo, CA

- Reusable Launch Vehicle Technology, An Overview of Rockwell's RLV Concept & Supporting Technologies, Affordable Access to Space, RLV Technology Readiness

22 June Aerospace Corporation El Segundo, CA

- Executive Summary, Discussion, Executive Briefings, Interim Report on the Space Surveillance, Space Debris and Near Earth Objects Committee, Space Technology & Space Applications, Presentation Rest-of-the-World Potential ASAT Capability

23 June Aerospace Corporation El Segundo, CA

- Teledesic Global Wireless Broadband Network: Space Segment Design Features & Technologies, Advanced Space Technologies for the 21st Century Current and Projected Threats to US Space Forces, Internationalization of Space Technology Planning for Future Space Consolidated Mission Architecture Study, Have Gaze, Tactical Imaging Constellation and Architecture Study (TICAS), Revolutionary Space Application Concepts, Hughes Satellite Control Facility Tour

14 July Beckman Center Irvine, CA

- Universities Space Research Association

Appendix D

List of Acronyms

Acronym	Definition
ACS	Attitude Control System
AFB	Air Force Base
AFOSR	Air Force Office of Scientific Research
AFS	Air Force Station
AFSPC	Air Force Space Command
AJ	Antijam
Al-Li	Aluminum/Lithium
ALEXIS	Array of Low-Energy X-ray Imaging Sensors
ALT	Anode Layer Thrusters
APS	Active Pixel Sensor
Ar	Argon
ASAT	Antisatellite
ASIC	Application-Specific Integrated Circuit
ASK	Accessible Stored Knowledge
ATM	Asynchronous Transfer Mode
ATR	Automatic Target Recognition
ATT	American Telephone and Telegraph
AU	Air University
BDA	Battle Damage Assesment
BIST	Built-In Self Test
BMDO	Ballistic Missile Defense Organization
C^3	Command, Control, and Communications
C^3I	Command, Control, Communications, and Intelligence
CCD	Charge-Coupled Device
CDMA	Code Division Multiple Access
CdTe	Cadmium Telluride

CIS	Copper Indium Diselenide
CMOS	Complementary Metal Oxide Semiconductor
CONUS	Continental United States
CORBA	Common Object Request Broker Architecture
COTS	Commercial Off-The-Shelf
CsI	Cesium Iodide
CsTe	Cesium Telluride
DAMA	Demand-Assigned Multiple Access
DBS	Direct Broadcast Satellite
DC	Direct Current
DoD	Department of Defense
DoE	Department of Energy
DRAM	Dynamic Random Access Memory
DSCS	Defense Satellite Communications System
DSP	Digital Signal Processing
EELV	Evolved Expendable Launch Vehicle
EHF	Extremely High Frequency
EMFB	Electromechanical Flywheel Battery
EMP	Electromagnetic Pulse
EO	Electro-Optical
EP	Electric Propulsion
EW	Electronic Warfare
FAA	Federal Aviation Adminisration
FLTSAT	Fleet Satellite
FORTE	Fast On-Orbit Recording of Transient Events
FOV	Field Of View
FY	Fiscal Year
GaAs	Gallium Arsenide
$GaInP_2$	Gallium Indium Phosphide
GaSb	Gallium Antinimide
Gbit	Gigabit

Gbps	Gigabit per Second
GEO	Geostationary Orbit
Gflop	Gigaflop
GHz	GigaHertz
GN&C	Guidance, Navigation, and Control
GPOW	Global Precision Optical Weapon
GPS	Global Positionsing System
H_2	Hydrogen
HEDM	High Energy Density Material
HEL	High Energy Laser
HF	High Frequency, or Hydrogen Fluoride
HLV	Heavy Launch Vehicle
IBC	Impurity Band Conduction
IBM	International Business Machines
ICBM	Intercontinental Ballistic Missile
IDA	Institute for Defense Analysis
IHPRPT	Integrated High-Payoff Rocket Propulsion Technology
InGaAs	Indium Gallium Arsenide
INMARSAT	International Maritime Satellite Organization
InSb	Indium Antinimide
IR	Infrared
IR&D	Independent Research and Development
I_{sp}	Specific Impulse
JPEG	Joint Photographic Experts Group
JPL	Jet Propulsion Laboratory
k	Kilo
K	Degrees Kelvin
kbit	Kilobit
Kbps	Kilobits Per Second
kg	Kilogram
KIPS	Kilo Instructions Per Second

KKV	Kinetic Kill Vehicle
Kr	Krypton
kW	KiloWatt
kWe	KiloWatt Electric
lb	Pound
LEASAT	Leased Satellite
LEO	Low Earth Orbit
LH_2	Liquid Hydrogen
LOX	Liquid Oxygen
LPI	Low Probability of Intercept
LV	Launch Vehicle
LWIR	Long-Wavelength Infrared
MAP	Mission Area Plan
Mbps	Megabits Per Second
MCM	Multi-Chip Module
MCP	Microchannel Plate
MCT	Mercury Cadmium Telluride
MEMS	Microelectromechanical Systems
Mflop	Megaflop
MFS	Multifunctional Structure
MILSTAR	Military Strategic and Tactical Relay
MIPS	Million Instructions Per Second
MIT	Massachusetts Institute of Technology
MJ	Megajoule
MLV	Medium Launch Vehicle
MMH	Monomethyl Hydrazine
MMIC	Multi-Module Integrated Circuit
MOS	Metal Oxide Semiconductor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MPA	Military Payload Assesment
MPD	Magnetoplasmadynamic

MPEG	Motion Pictures Experts Group
MRAM	Magnetoresistive RAM
MSE	Mobile Subscriber Equipment
MTI	Moving Target Indicator
MW	MegaWatt
NH_3	Amonia
N_2H_4	Hydrazine
N_2O_4	Nitrogen Tetraoxide
NASA	National Aeronautics and Space Administration
NiH_2	Nickel-Hydrogen
NRO	National Reconnaissance Office
PERS	Polycynate-Ester Resin Systems
PL	Phillips Laboratory
PPT	Pulsed Plasma Thruster
QWIP	Quantum Well Infrared Photodetector
RAM	Random Access Memory
RF	Radio Frequency
RFI	Radio Frequency Interference
RL	Rome Laboratory
RLV	Reusable Launch Vehicle
RTG	Radioisotope Thermionic Generator
S&T	Science and Technology
SAB	Scientific Advisory Board
SAR	Synthetic Aperture Radar
SAWAFE	Satellite Attack Warning and Assesment Flight Experiment
SECAF	Secretary of the Air Force
SDIO	Strategic Defense Initiative Organization
SHF	Super High Frequency
SIOP	Single Integrated Operations Plan
SMC	Space and Missiles Systems Center
SNL	Sandia National Laboratory

SOI	Silicon On Insulator
SPT	Stationary Plasma Thruster
SRAM	Static Random Access Memory
SSTO	Single Stage To Orbit
STS	Space Transportation System
TAOS	Technology for Autonomous Operational Survivability
TAV	Trans-Atmospheric Vehicle
TDM	Time-Domain Multiplexed
TDMA	Time Division Multiple Access
TENCAP	Technical Exploitation of National Capabilities
TICAS	Tactical Imaging Constellation and Architecture Study
TOA	Total Obligation Authority
TT&C	Telemetry, Tracking, and Control
TV	Television
UAV	Unmanned Air Vehicle
UHF	Ultra High Frequency
US	United States
USAF	United States Air Force
UV	Ultraviolet
VLSI	Very Large Scale Integration
Wh	Watt-Hour
Wh/kg	Watt-Hour per Kilogram
Xe	Xenon
µm	Micrometer

Appendix E

Relevant Space Technology Studies and Reports

E.1 Spacecast 2020

The Spacecast 2020 study was conducted by Air University in 1994. The study was conducted to identify capabilities for the period of 2020 and beyond and the technologies to enable them that will best support preserving the security of the United States. The study considered the full vertical dimension, including the important region of the transatmosphere that both separates and integrates air and space. The study identified the most important reason to be in space as having the global presence required to maintain global view. Global presence and global view are the enablers for Global Reach, Global Power. The implementation of global presence and the concept of global view depend on:

- An integrated, on-demand information system
- Increased and improved sensing capabilities
- Relatively inexpensive spacelift

Two Spacecast system concepts showed the greatest potential for enhancing space operations:

- Transatmospheric vehicle (TAV)
- Space-based high-energy laser (HEL) system

The study assessed technologies by considering the number of systems each technology supported, the degree to which each system depended on it, and the importance of the system. Three technologies stood out because they were important to a large number of high-value systems:

- High-performance computing
- Micro-mechanical devices
- Navigation, guidance, and vehicle control

Three other technologies were also important, but to a smaller range of systems. These technology areas showed promise to open the way to space systems that would dramatically improve the effectiveness of space operations. These technologies are:

- Materials technology
- Pulsed power systems
- Robotics, controllers, and end-effector

E.2 Space Systems Technology Working Group

The purpose of the Space Systems Technology Working Group (SSTWG) was to identify those technologies that were space-unique, military-critical, and dual-use to provide the basis

for policy and priority decisions regarding technology support, cooperative agreements, and export controls. The SSTWG identified and described the military-critical space technologies (using service mission deficiencies as a major input), explained their military significance, identified the key quantitative parameters involved, estimated their dual-use potential, assessed their foreign availability, defined more completely the threshold specifications in order to free from control those technologies that were not militarily critical, and discussed the economic security implications of the critical military and dual-use technologies. The SSTWG concluded:

- All services need an integrated space mission area road map to provide a firm basis for space technology planning and prioritization.
- Modifications to the development process techniques of systems engineering and integration as applied to space systems (defining, developing, manufacturing, integrating, testing, launching and on-orbit operations) have significant potential for greater efficiencies, cost saving, assured access to space, and continued US space leadership.
- Forty technologies of the 116 military-critical space technologies identified and categorized as critical space-unique should be recognized as such in the appropriate DoD documentation. Thirty-six technology areas were considered high payoff areas and candidates for additional investment.
- Payload modules, buses, and interfaces must be standardized to improve technology insertion and provide improved interoperability and savings within the military and commercial space community.
- Selling the products of space technology or on-orbit capabilities rather than selling the specific technology had the significant potential of protecting the US job and production base and associated development and production technologies.

The SSTWG recognized space as a unique environment that provides unparalleled military operational advantages. To withstand space environmental conditions, components must operate in conditions of extreme thermal cycling and radiation exposure and with lifetimes that are measured in years instead of days or weeks. Technologies were divided among 12 subgroups: space systems integration, launch vehicles, structures, propulsion, power and thermal management, communications, electronics and computers, astronautics, sensors and surveillance, optics, vulnerability and survivability, and qualification and testing.

E.3 Seven Strategies for Space

This study identified actions to improve mission accomplishment (global presence in the post cold war world) and to improve resource allocation. The study was conducted because of the need for a comprehensive reexamination of the US space program in light of the changing world environment and reduced resources. The seven strategies included:

- Establish a comprehensive architecture
- Provide an interactive forum for space operations and modernization
- Integrate the requirements processes

- Spearhead joint training
- Adopt horizontal engineering
- Exploit combined test
- Develop new partnerships with industry

E.4 Space Launch Ad Hoc Study

This study was a Scientific Advisory Board study with the following objectives:

- Assess the state of current launch systems, including infrastructure, and define the deficiencies in the current systems
- Review concepts and technologies for improvement of the present and future launch systems, expendable and reusable
- Select approaches which address the shortfalls of current systems, show the merit of those approaches, and identify technologies related to those approaches
- Recommend technology options for reducing development, production, operation, and support costs while supporting reliability and operational flexibility
- Develop a transition strategy from the current launch vehicle inventory to one taking fullest advantage of the most promising concepts and technologies

Deficiencies included costs, responsiveness, scheduling, and reliability. The study found that most of the space launch community did not believe that responsiveness was a major problem. Spacecraft constellations were viewed as robust and offering some flexibility in replacing nonfunctional systems. Some satellites were seen to be so complicated and expensive that a launch delay would be acceptable if changes of successful on-orbit operation would be enhanced. Existing launch systems were found to be significantly limited by design in their ability to provide responsive launch capability. Responsiveness was identified not as a technology limitation, but as a design issue.

The study found that commercial distributed satellite systems will likely bring about a paradigm shift in launch vehicle design, manufacturing and operations, driven by several factors:

- There may be a rapidly growing market for medium to medium- heavy launch vehicles for payload delivery to low altitude orbit
- There will be a market for smaller launch vehicles for constellation maintenance
- There will be a premium on launch on schedule, simple standardized operations, and quantity production
- There is the potential for a larger (factor of two increase) market for medium launch vehicles and facilities that will incentivize improvements
- The trend toward distributed systems may extend to the military

The study called for an examination of the technology drivers in propulsion, vehicle design and operations for:

- Existing launch vehicles
- A new, expendable medium-lift vehicle
- Partially reusable, medium-lift vehicles
- All solid rocket booster
- Single State to Orbit (SSTO) and/or totally reusable systems

Reusable Launch Vehicles (not necessarily single-stage-to-orbit) were identified as the ultimate answer to affordable launch capability.

The panel study recommendations for new launch vehicles included:

- Emphasizing technology development programs needed to resolve questions about the cost, risk, schedule, and feasibility of reusable and partially reusable systems
- Developing any new launch system with standardized payload interfaces, utilizing encapsulated payloads, and minimizing on pad operations
- Including technology demonstrations prior to committing to the development of any new space launch vehicle
- Exploiting the advantages of modular systems in the development of a new launch vehicle

The panel recommended the following high priority investments: clean solids, upper stages, high-energy fuels, storable propellants, and low-cost engines and components.

E.5 Recent DoD Space Launch Studies

The years 1992, 1993, and 1994 were marked by several studies on the issue of space launch. In 1992, Pete Aldridge, former Secretary of the Air Force, led a study effort on behalf of Vice President Quayle and the National Space Council. This study became known as the Aldridge report. In early 1993, NASA responded to Congressional tasking with its own Access to Space Study, which included both NASA and DoD requirements. Almost simultaneously DoD announced its own plans to conduct a "Bottom-Up Review" of space launch requirements. Most recently, Congress (in the FY94 Defense Authorization Act) directed DoD to accomplish yet another space launch study. This study, known as the Moorman Study, was able to achieve consensus within NASA, DoD, the Intelligence community, and the US commercial sector on the needed direction for space launch. The Moorman study was the basis for President Clinton's August 1994 Space Transportation Policy. Each of the foregoing studies is briefly reviewed, highlighting the technology recommendations each made.

E.5.1 Aldridge Report

The Aldridge study focused on the leadership issue for space launch, recognizing that past failures to build a national consensus were the result of too many actors in this arena. The report suggested that a "Space Czar" position should be created, a recommendation that was never

seriously considered. As a near term solution to the nation's needs, the report suggested that the Air Force "spacelifter" program be adopted to solve the nation's medium lift needs (up to 20,000 lb to LEO). The Aldridge report recognized that technology is a vital part of the path to the future. A major finding of the Aldridge report was "the technology efforts associated with NASP, SSRT, and HSCT are essential for application to future generations of fully reusable space launch vehicles."[5] The report referenced the ten-year DoD space launch technology plan and indicated that the needed national level of investment in launch technology was on the order of $700M.

E.5.2 NASA Access to Space Study

This study was completed in the summer of 1993. It examined three options for solving the nation's space launch needs. Option 1 maintained the Shuttle and the expendable launch vehicle (ELV) fleet until the year 2030. Option 2 examined developing a new expendable launch system using state-of-the-art technology with a transition date of 2005. Option 3 contained a new, advanced-technology, next-generation reusable launch system and associated technology demonstration program with an operational transition date of 2008. NASA recommended adoption of Option 3. The Executive Summary for Option 3 identified five enabling technologies for the three reusable vehicle options identified in the report. These technologies are:

- Reusable cryogenic tanks
- Vehicle health management and monitoring
- Autonomous flight control
- Operations enhancements
- Long-life/low maintenance thermal protection systems

E.5.3 OSD Bottom-Up Review

The OSD Bottom-Up Review also examined the nation's space launch needs and came to a very different conclusion than NASA. Similar to NASA's study, the OSD Bottom-Up Review examined three options: Alternative 1 considered using today's launch systems; essentially a life extension of the current expendable DoD fleet, Alternative 2 studied the development of a new launch system (included SSTO), and Alternative 3 examined the so-called "leapfrog" reusable launch system options. Leapfrog technology included fly-back first stage, two-stage-to-orbit, and airbreathing rocket single-stage-to- orbit. For primarily affordability reasons, OSD adopted Alternative 1. Alternative 3 identified a list of technologies required:[6]

- Thermal protection systems
- Expander engine with high I_{sp}
- Graphite epoxy truss and tank

5. The Future of the U.S. Space Launch Capability, Vice President's SpacePolicy Advisory Board, November 1992
6. DoD Space Launch Systems Review, prepared by SMC, 15 April 1993 and Space Launch Systems Bottom-Up Review, briefing prepared by the Director, Strategic & Space Systems, 4 May 1993

- Lightweight metallic tiles
- Landing software
- Hypersonic air breathing propulsion

E.5.4 Moorman Study

A strength of the Moorman study was the effort to include both governmental and commercial space sectors in requirements and investment process. Importantly, the study group came to a consensus on a construct for characterizing the nation's top level launch system requirements. They adopted the CORE model to specify vehicle characteristics: Capable, Operable, Reliable, Economical.

Rather than try to solve the leadership problem by taking equities away from the various sectors, the Moorman study strove to play to sector strengths. To that end, the study recommended that NASA be placed in charge developing the nation's reusable technology. Given the expense of operating the Shuttle fleet, it was judged that reusability and the promise of lower operating costs were vital to NASA in light of its International Space Station venture. Similarly the study recommended that DoD be placed in charge of evolving the nation's expendable launch fleet. This arrangement was later ratified in President Clinton's 1994 Space Transportation Policy Directive. The Moorman study examined four options:

- Baseline President's FY95 budget - continued existing fleet (STS, Delta, Atlas, and Titan)
- Evolved Expendable Launch Vehicle (EELV) option
- "Clean Sheet" ELV option
- Reusable option

The study did not make explicit recommendations, but suggested a two pronged approach to solving the nation's problem: DoD should lead the EELV option and NASA should lead the reusable option. Importantly, the report noted that DoD's space launch technology effort was underfunded and recommended an annual investment on the order of $90M to $120M.

Appendix F

White Papers Received by the Space Technology Panel

(Arranged Alphabetically by Organization)

Aerospace Corp.
28 Jun 95
Mr. Jay Penn

- SSTO Feasibility

Air Force Institute of Technology
26 Apr 95
Dr. William E. Wiesel

- Access to Space

Air Force Office of Scientific Research (AFOSR)/NL
23 Jun 95
Dr. Michael Berman

- High Energy Density Materials

AFOSR/NL
23 Jun 95
Dr. Michael Berman

- Characterization and Scale-Up of HEDM Materials Leading to Increase in Specific Impulse Over Current Propulsion Systems

AFOSR/NA
8 Jun 95
Dr. Mitat Birkan

- Space Propulsion Concepts and Missions

AFOSR/NA
6 Jul 95
Dr. James McMichael

- Microelectromechanical Systems (MEMS)

American Institute of Aeronautics and Astronautics, Inc. and Space Studies Institute
22 May 95
Dr. Tidman, Dr. Burton, Dr. Jenkins, Dr. Witherspoon

- Sling Launch of Materials into Space

John Hopkins University Applied Physics Laboratory
22 May 95
Dr. Vincent Pisacane

- Spacecraft Technology Investment Strategy

Howard University
25 Apr 95
Dr. Peter Bainum, Dr. Feiyue Li, Prof. Guangqian Xing,
Dr. Jianke Xu, Mr. ZhaoZhi Tan, Mr. Raj Kotaru, Ms. Aprille Ericsson, Mr. Raj Pai, Ms. Phyllis Jones

- New Technologies that will Lead to Fundamental Improvements in Space Applications

Howard University
25 Apr 95
Dr. Peter Bainum, Dr. Feiyue Li, Prof. Guangqian Xing, Dr. Jianke Xu, Mr. ZhaoZhi Tan, Mr. Raj Kotaru, Ms. Aprille Ericsson, Mr. Raj Pai, Ms. Phyllis Jones

- Technologies that will Enable New Applications in Space - Tethered System Applications

Iowa State University
27 Apr 95
Dr. John Basart

- Non-Destructive Evaluation of Space Structures

Iowa State University
1 May 95
Dr. Bill Byrd

- Space Technology - The Next Ten to Thirty Years

Iowa State University
1 May 95
Prof. David Holger

- Space Technology for New World Vistas

Feb 95
Allen Thomson

- Satellite Vulnerability: A Post-Cold War Issue? *Space Policy,* Feb 95

NASA
12 Jun 95
Mr. Ivan Bekey

- Future Space Technologies

NASA
4 Jan 94
Mr. Ivan Bekey

- Why SSTO Rocket Launch Vehicles Are Now Feasible and Practical

NETROLOGIC, Inc.
24 May 95
Dr. Dan Greenwood

- "A Proposed Plan for a Lunar-based Power Plant," *Science & Technology in Japan,* Vol 14 (95-1), No 53

Phillips Lab (PL)/GP
14 Jul 95
Dr. Richard Hendl

- Sensing the Space Environment

PL/GPA
11 May 95
Dr. Arnold Barnes, Jr.

- Weather Modification

PL/GPI
11 May 95
Dr. Dave Gleason

- Precise Tracking & Targeting Satellite Networks

PL/GPI
20 Jul 95
Dr. Robert Huffman

- State of the Art of Ultraviolet Detectors

PL/GPS
11 May 95
Dr. Gregory Ginet

- Space Particle Modification for Defense/Offense

PL/RKF
17 May 95
Dr. Stephen Rodgers, Dr. Patrick Carrick

- Positive Enthalpy Hydrocarbons as RP-1 Additives

PL/VT-X
10 Jul 95
LtCol J. M. Sponable

- Assessing Single Stage To Orbit Feasibility

PL/WSSI
17 May 95
Mr. Charles Pike

- Counterproliferation Sensing Technology: Conductive Polymers

PL/VT-X
17 May 95
Capt Fred Kennedy

- The Integrated Solar Upper Stage (ISUS) Program

PL/LIA
17 May 95
Dr. Paul Merritt

- MEMS Technology for Adaptive Optics

PL/RK
17 May 95
Mr. Wayne Pritz

- Low Cost Space Launch

PL/RK
17 May 95
Mr. Glenn Olson

- POGO Spacelift Concept

PL/RK
17 May 95
Dr. Steve Rogers

- High Energy Density Materials

Science Applications International Corportation (SAIC)
22 Jun 95
Maj Gen (R) Robert Rosenberg

- Future Military Space Systems and the Principles of War (Draft)

SAIC
22 Jun 95
Maj Gen (R) Robert Rosenberg

- Possibilities for the Use of Current & Emerging Technologies to Enhance Future Warfighting Capabilities Using Space Systems (Draft)

Texas Center for Superconductivity at the University of Houston
20 Jul 95
Z. Xia, K. B. Ma, Q. Y. Chen, R. S. Cooley, P. C. Fowler, C. K. McMichael, W. K. Chu

- Hybrid Superconducting Magnetic Bearing & Its Frictional Energy Loss and Dynamics

University of Florida
18 Apr 95
Dr. Norman Fitz-Coy

- Recycling to Reduce Space Debris

University of Florida
18 Apr 95
Dr. Gale Nevill

- Closed-Loop Life Support Systems

University of Florida
18 Apr 95
Dr. Malcolm Shuster

- Manufacturing Methods for Complex Systems

University of Florida
18 Apr 95
Dr. Malcolm Shuster

- Smart Sensors

University of Florida
18 Apr 95
Dr. Wei Shyy

- Cost to Launch Demands Improved Propulsion Efficiency

University of Florida
18 Apr 95
Dr. Wei Shyy

- Higher Resolution Observation Requires Improved Thermal Management

University of Illinois at Urbana-Champaign
12 May 95
Prof. R.L. Burton, Prof. J. Economy, Prof. W. K. Jenkins, Prof. G. Papen, Prof. L. H. Sentman, Prof. S. White

- Technology Areas for AF Space Mission

University of Maryland
5 Jul 95
Dr. Preston Carter, Dr. Darryl Pines

- A Comparison of the Hypersoar Trajectory with Traditional Hypersonic Trajectories

Appendix G

Briefings Received by the Space Technology Panel

16 Mar 95 Falcon AFB,CO

Dr. Gene McCall
LANL
- New World Vistas Overview

Mr. Lowell Wood
LLNL
- Roles & Missions of the US Space Force

Col Henry Pugh
PL/VT
- Future Space Technologies - AFSPC View

Maj Kurt Stevens
AFSPC/XPX
- Space & Missile S&T Overview

17 Mar 95 Falcon AFB,CO

Mr. Gareth Flora
Lockheed Martin
- Launch Vehicle Technology Perspective

Mr. Clovis Landry
Lockheed Martin
- Spacecraft Technologies - In Support of a New Reality

Maj Calvin Johnson
SWC/DO
- TENCAP

13 Apr 95 Phillips Laboratory,
Kirtland AFB, NM

Col Richard Davis
PL/CC
- Introduction and Welcome

Dr. Greg Canavan
LANL
- Overview

Dr. Mark Hodgson
LANL
- ALEXIS

Dr. Steve Knox
LANL
- FORTE

Dr. Paul Weber
LANL
- Multi-Spectral Thermal Images Experimental Space System

Dr. Richard Epstein
LANL
- Fluorescent Refrigerator

Dr. Bill Saylor
LANL
- SAWAFE

Dr. Frank Mead
PL/RK
- Advanced Propulsion Concepts

Ms. Liz Shinn
WL
- Advanced Materials Development

LtCol Dave Kristensen
PL/VTP
- Nuclear Power/Propulsion/Bimodal/Space Power

Mr. Frank Fisk
PL
- Space Communications

Capt Jose Colon
PL
- Space Sensors

Col Mike Havey
PL/SX
- Space Experiments

Dr. Janet Fender
- Directed Energy Applications

14 April Phillips Laboratory,
Kirtland AFB, NM

Capt Mitch Clapp
PL/VT
- Reusable Launch Vehicles/Technologies

Capt Ron Marx
PL
- Space Electronics

LtCol Nancy Crowley
PL
- Satellite Control

Capt Mark Snyder
PL
- Space Structures

Mr. Kevin Slimak, Mr. Bob Vacek, Col Henry Pugh
PL
- Technology Integration

Dr. Gerry Yonas
SNL
- Space Technology Programs

10 May Lincoln Laboratory, MA

MIT Grad Students
MIT
- Innovative Space Technologies and Applications

Col Richard Szafranski
AU
- Spacecast 2020

Mr. Sam Venneri
NASA
- NASA Perspectives

Mr. Dave Hornback, Lt Jim Shell
FAIC
- International Activities

Mr. Darryl Sargent
C. S. Draper labs
- Technologies for Space Applications

Dr. Roy Bondurant
Lincoln Lab
- Space Laser Communications

Dr. Dan Kostishack
Lincoln Lab
- Space Sensor Technology (Electroptical)

Dr. Steven Bernstein
Lincoln Lab
- DoD Satellite Communication

Dr. Charles Holland
AFOSR
- Air Force Basic Research

11 May Lincoln Laboratory, MA

Maj Suddarth
BMDO
- BMDO Technologies

Mr. Larry Newman
Astrospace
- Navigating a 3-D Technology Roadmap

Dr. Richard Hendl
PL/GP
- Geophysics Technologies Overview

Dr. Gregory Ginet
PL/GPS
- Space Particle Modification for Defense/Offense

Dr. Dave Gleason
PL/GPI
- Precise Tracking and Targeting Satellite Networks

Dr. Arnold Barnes, Jr.
PL/GPA
- Weather Modification

12 May Lincoln Laboratory, MA

Dr. Laila Jeong
PL/GPO
- Multispectral, Hi-Resolution Sensors

Dr. Tony Pensa
MIT
- Haystack Observatory

Dr. Antonio Elias
Orbital Sciences Corp
- Launch Vehicles

Col (R) Kirk Lewis, MGen (R) Gerald Hendricks
IDA
- Space Critical Technologies

Mr. Ivan Bekey
NASA
- Innovative Concepts

21 Jun 95 Jet Propulsion Laboratory

Dr. Carl Kukkonen
JPL
- Overview - Sensor and Information Processing Technology

Dr. Dave Collins
JPL
- Second Generation Microspacecraft Study

Dr. Tim Krabach
JPL
- Hyperspectral Imaging Systems

Dr. Fook Lee
JPL
- Synthetic Aperture Radar (SAR)

Dr. Barbara Wilson
JPL
- JPL Tour

21 Jun 95 Aerospace Corporation

LtCol Jess Sponable
PL/VT
- Reusable Launch Vehicle Technology

Mr. Tom Healy
Rockwell Aerospace
- An Overview of Rockwell's RLV Concept & Supporting Technologies

Lockheed-Martin Skunk Works
- Affordable Access to Space

Mr. Bruce Leonard
McDonnell-Douglas Aircraft
- RLV Technology Readiness

22 Jun 95 Aerospace Corporation

Dr. Yarymovych
Rockwell
- Executive Summary Discussion

Prof. Hastings
MIT
- Executive Briefings

Dr. Greg Canavan
SAB Ad Hoc Committee
- Interim Report on the Space Surveillance, Space Debris and Near Earth Objects Committee

Dr. Thomas Brackey
Hughes
- Space Technology & Space Applications Presentation

Mr. Donald Winter
TRW
- Space Technology & Space Applications Presentation

Mr. Andrew Johnson
Rockwell
- Rest-of-the-World Potential ASAT Capability

23 Jun 95 Aerospace Corporation

Dr. James Stuart
Teledesic
- Teledesic Global Wireless Broadband Network: Space Segment Design Features & Technologies

Dr. Anthony Sutey
Boeing Defense and Space Group
- Advanced Space Technologies for the 21st Century

Mr. George Rock
Aerospace Corporation
- Current and Projected Threats to US Space Forces

Dr. Donald Lewis
Aerospace Corporation
- Internationalization of Space Technology

Col Robert Preston
SMC/XRT
- Planning for Future Space

Dr. Donald Lewis
Aerospace Corporation
- Consolidated Mission Architecture Study

Dr. Martin Balser
XonTech
- Have Gaze

Col Rustan
SAF
- Tactical Imaging Constellation and Architecture Study (TICAS)

Mr. Samuel Araki, Mr Albert Smith
Lockheed-Martin
- Revolutionary Space Application Concepts

Hughes Communications
- Hughes Satellite Control Facility Tour

11 July Irvine, CA

General (R) Charles Horner
- Discussion

12 July Irvine, CA

General (R) Donald Kutyna
- Discussion

14 July Irvine, CA

Dr. Paul Coleman, Jr.
USRA
- Universities Space Research Association

17 July Irvine, CA

Maj Gen George Muellner
SAF/AQ
- Discussion